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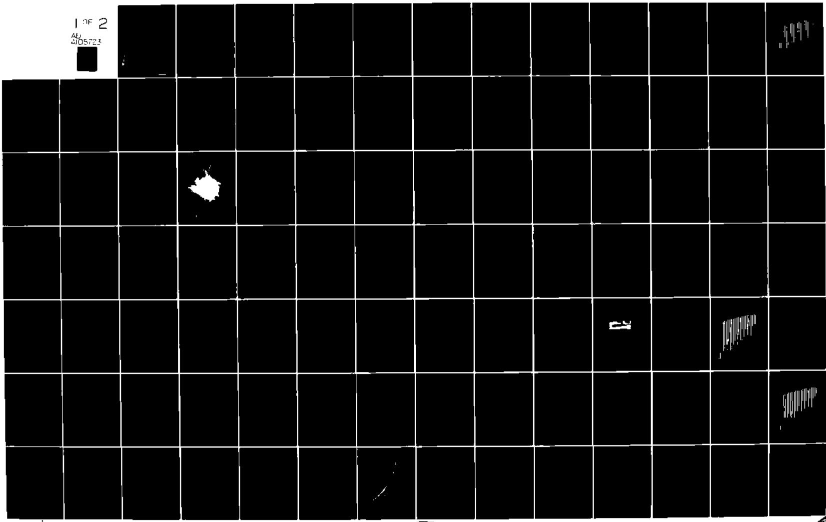

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SEPTEMBER 1981

Secondary Fire Analysis

FINAL REPORT

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Contract No. EMW-C-0369
Work Unit 2564I

SCIENTIFIC SERVICE, INC.

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This report presents the results of a program to examine the potential for secondary fires (i.e., those caused by blast or other nonthermal effects of a nuclear detonation) in or near structures, with emphasis on critical facilities and industries. Assessment of the potential for secondary fires is critical to many aspects of civil defense planning: protecting against ignitions in critical/key industries, protecting from fire spread, assessing expected damage, and locating or determining the survivability of key worker shelters.

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There are significant differences between the secondary ignitions caused by nuclear blasts and those caused by other mechanical stimuli such as earthquakes. This fact greatly reduces the data base available to apply to the development of a prediction method.

A model, developed for use by civil defense planners, is detachable from the report for easy use in field surveys. The input provided includes all information required to determine the key parameters: the building type, its structural characteristics, a use classification, damage as a function of overpressure, and the probability of secondary fires.

(DETACHABLE SUMMARY)

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SECONDARY FIRE ANALYSIS

by

C. Wilton, D.J. Myronuk, and J.V. Zaccor

for

Federal Emergency Management Agency
Washington, D.C. 20472

Contract No. EMW-C-0369, Work Unit 2564I
Captain Richard E. Peterson, Project Officer

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Scientific Service, Inc.
517 East Bayshore, Redwood City, CA 94063

(DETACHABLE SUMMARY)

SECONDARY FIRE ANALYSIS

This report presents the results of a program to examine the potential for secondary fires in or near structures, with emphasis on critical facilities and industries. Secondary fires are defined as fires caused by blast effects, or other nonthermal effects, of a nuclear detonation, in contrast with primary fires, which are those resulting from the thermal radiation of a nuclear detonation.

Assessment of the potential for secondary fires is critical to many aspects of civil defense planning, including protection against ignitions in critical/key industries, protection from fire spread, assessment of expected damage, and for locating or for determining the survivability of key worker shelters.

The specific work accomplished under this program was to review and assess a broad range of available data on fire ignitions from secondary (nonthermal) causes encompassing: nuclear explosions (Hiroshima, Nagasaki, and the Nevada tests); natural disasters (earthquakes, hurricanes, tornadoes, etc.); explosions (high explosive tests and accidents); and available research documents.

The major findings of this study were that there are significant differences between the secondary ignitions caused by nuclear blasts and those caused by other mechanical stimuli such as earthquakes. This fact greatly reduces the data base available to apply to the development of a prediction method. The results of the study indicate that, in the 2 to 5 psi range, secondary ignitions from megaton weapons are probably inconsequential compared with primary ignitions, while in the 0.5 to 3 psi range (a vastly larger area than the 2 to 5 psi range), secondary ignitions may prove very important.

A model has been developed, using the limited data base available. This model was designed for use by civil defense planners, and the input provided includes all information required to determine the key parameters. These parameters include the building type, its structural characteristics, a use classification, damage as a function of overpressure, and the probability this will lead to secondary fires. A copy of this model has been made detachable from the report for easy use in field surveys.

THE MODEL

In the report the development of the secondary fire prediction model was described. These pages, which can be easily adapted into a field use package, explain the use of the model.

All necessary data are supplied, with the exception of the psi level to be expected at the facility. It is not known at this time whether definitive predicted psi information will be available from local civil defense authorities in all areas. If none is available it will be necessary to assume the worst, such as heavy damage, for the prediction procedure. If a crisis relocation plan has been developed, however, it will usually include an evacuation zone. The outer boundary of this zone is usually established at the 2 psi ground range (or in some rare cases 3 psi) from a predicted attack. Using this boundary line and distances from the line, either toward or away from the attack point, it is possible to extrapolate a predicted psi value for a particular location and weapon size. (A representative range of sizes is 1 to 20 MT.) To aid in extrapolating from this line refer to Figure A, which gives the ground ranges for various sizes of megaton weapons for overpressures from 15 to 0.1 psi.

The steps in using the model are shown on the worksheet, Figure B. They are as follows:

1. List facility name and address or identification number.

2. Identify type of occupancy (machine shop, etc.)

3. Select construction type from building index in Table A and Figure C (e.g., sheet metal storage shed = 10; concrete block warehouse = 8, etc).

4. From Step 2, type of occupancy, select contents index number from Table B (custom machine shop = 4.1; service station = 8.2, etc.). Note, for multi-use facilities, either divide facility and make estimates for each occupancy area, or use most hazardous occupancy (i.e., higher contents index number). Also, if hazardous/flammable/combustible materials are in a protected location (e.g., behind firebreak or underground) make contents index one point lower; i.e., service station becomes 7.2 instead of 8.2.

5. List expected overpressure at the facility, either obtained from civil defense sources or extrapolated from Figure A.

6. Select appropriate damage level (light, medium, or heavy) from index using expected overpressure and overpressure damage estimate from Figure C.

7. Using a straight edge, line up selected building index with contents index, and extend to intersect the appropriate damage index on alignment chart, Figure D. Read predicted secondary fire estimate on right side of damage index and record on worksheet (Figure B).

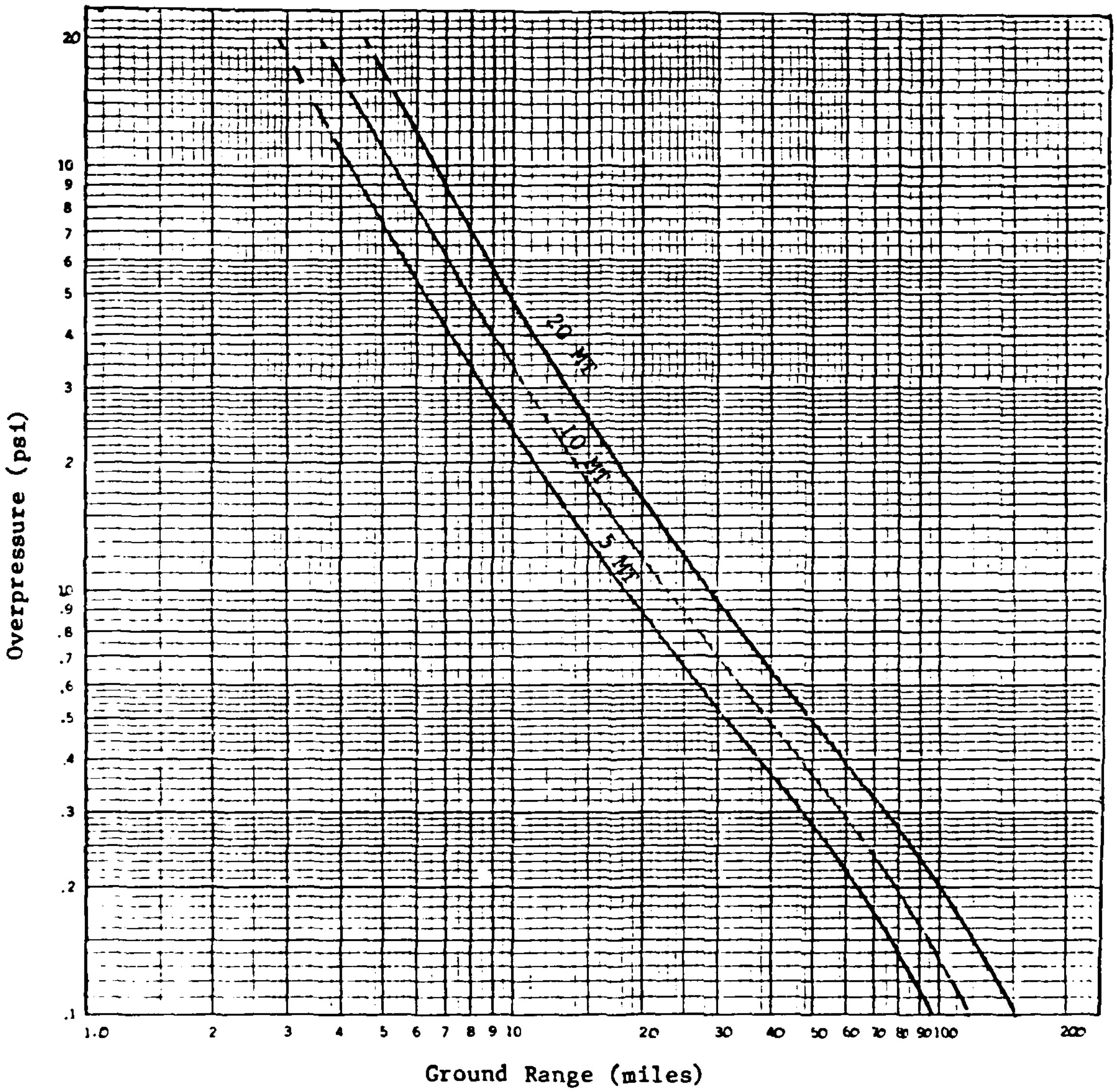

Fig. A. Pressure-Distance Falloff Curves for Bursts Intermediate Between Surface and Optimum Height.

1	2	3	4	5	6	7
FACILITY NAME OR NUMBER	FACILITY TYPE	BUILDING INDEX	CONTENTS INDEX	EXPECTED OVER PRESSURE (PSI)	DAMAGE LEVEL	NUMBER OF FIRES PER UNIT

Fig. B. Worksheet

TABLE A: BUILDING INDEX

1. **Heavy Design**
   Reinforced concrete structures designed for protective purposes (e.g., bank vaults, nuclear containment vessels and control rooms)

2. **Heavy Design**
   Reinforced concrete walls, roofs, and floors or heavy steel frame, metal deck supported by steel purling, with reinforced concrete topping; walls of concrete block or brick (e.g., heavy manufacturing, power plants, storage warehouses)

3. **Heavy Design**
   Reinforced concrete frame with precast concrete walls, floors, and roof; or heavy timber frame with heavy timber floor and walls of concrete block or brick (r.g., heavy manufacturing, office buildings, warehouses)

4. **Medium Design**
   Precast concrete frame with precast walls, floors, and roof, or heavy timber frame with medium loading floors and walls of concrete block or brick, or medium design reinforced concrete walls, floors, and roof (e.g., light manufacturing, large retail or wholesale stores)

5. **Medium Design Load**
   Concrete block or brick wall, precast concrete floors/roof, with wall openings of more than 10% (light manufacturing, retail and wholesale stores, light storage warehouses)

6. **Medium Design Load**
   Concrete block or brick walls, precast concrete roofs/floors with less than 15% wall openings; precast concrete walls with precast concrete floors and roofs (pumphouses, mechanical equipment buildings, storage buildings, water and sewage treatment plants, light manufacturing)

7. **Light Design Load**
   Concrete block or brick walls, timber roofs and floors with more than 15% openings in walls (retail stores, motels, professional buildings, office buildings)

8. **Light Design Load**
   Concrete block or brick walls, timber roofs and floors with less than 15% wall opening (mini warehouses, construction storage buildings)

9. **Light Design**
   Precast concrete walls with timber joist roofs and floors or steel joist roof and floors; light steel frame, infill walls with steel joists and roofs (warehouses, office buildings, and light manufacturing)

10. **Light Design**
    Wood/metal stud walls, with siding, stucco, brick veneer; timber joist or glulam roofs and floors; light corrugated metal walls and roofs (residences, restaurants, small retail stores, storage sheds, light manufacturing)

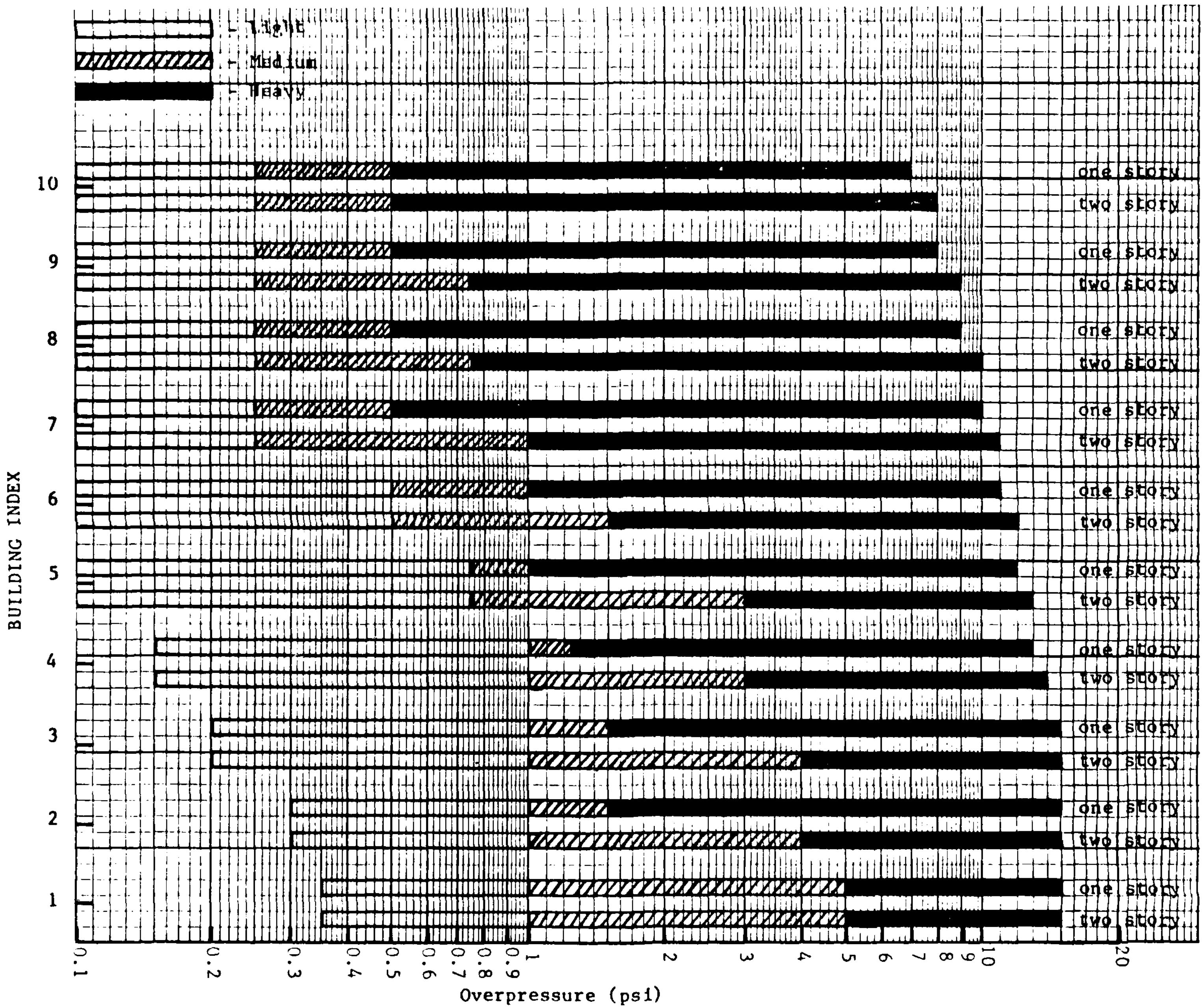

Fig. C. Building Index vs Degree of Damage at Various Overpressures.

TABLE B: CONTENTS INDEX

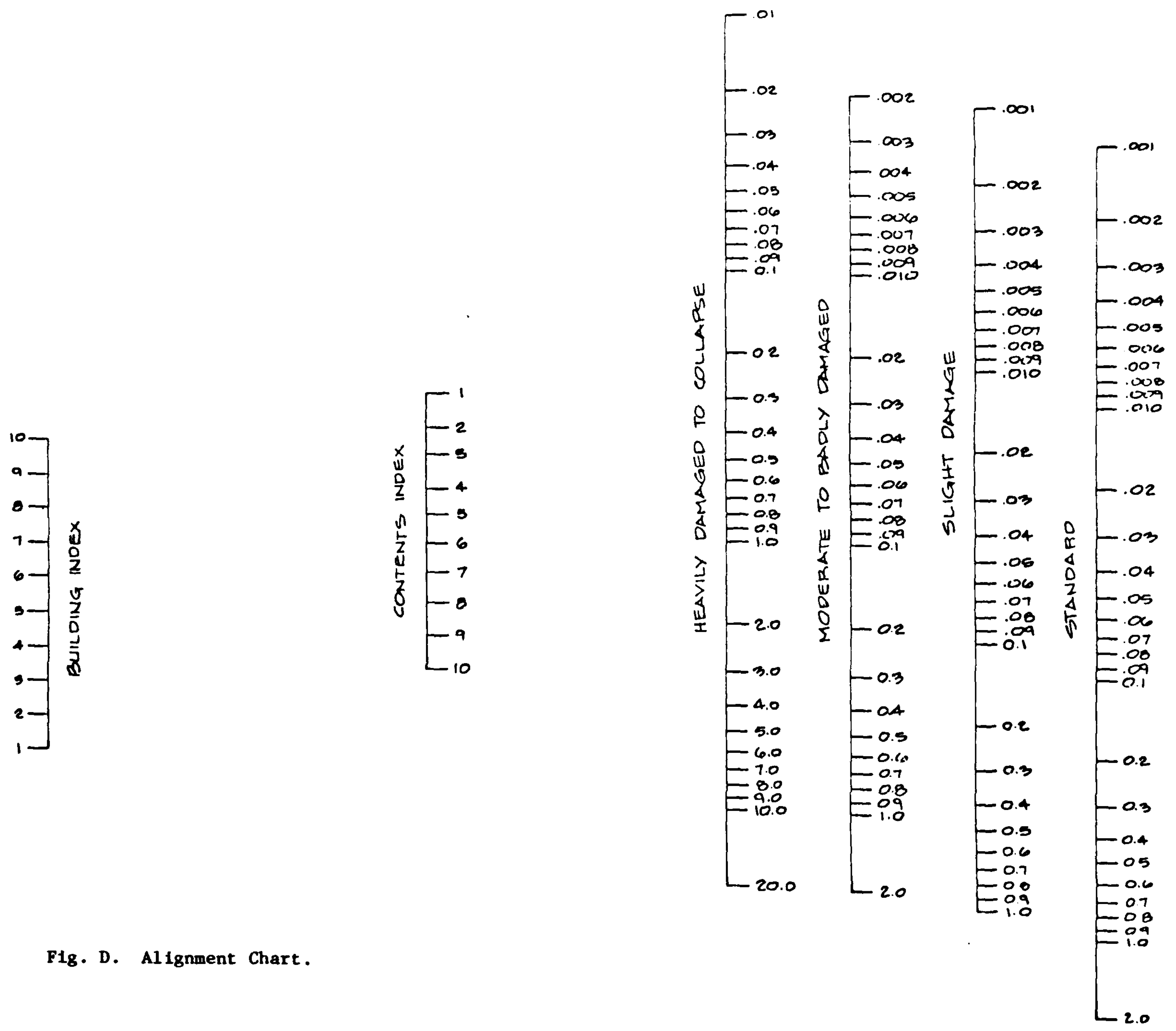

Fig. D. Alignment Chart.

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Acknowledgements

This report discusses secondary fires in relation to primary ignitions, identifies where they are likely to be the dominant mechanism, and provides a prediction procedure. The authors wish to take this opportunity to thank all those involved in completing this project. We particularly wish to thank Captain Richard E. Peterson and James W. Kerr of the Federal Emergency Management Agency for their overall project direction; Dr. B.L. Gabrielsen, of San Jose State University, and R.S. Tansley and R. Reitherman from SSI for their contributions to development of concepts and basic data and information; and the support staff, Larue Wilton, Evelyn Kaplan, Maureen Ineich, Michael Reeder, and Lynn Hubenette for their patience as well as their talents.

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Section 1
INTRODUCTION

Background

Civil Defense planning in the United States is currently based on a policy termed "Crisis Relocation". This policy presumes that a period of crisis buildup in the world — similar to the Cuban and recent Middle East crises — will precede any future war. This period of crisis would allow time (a few days or weeks) to complete a number of activities to protect the civilian population and industry from attack. These activities include:

> Evacuation of the major portion of the population to low-risk areas where only fallout and possibly low level blast protection would be required.
>
> Protection of a small contingent of key workers who would remain behind to maintain vital services - communications, fire protection, etc.
>
> The hardening and protection of critical industries and facilities.

Recently, considerable research has been devoted to the protection of industry (for example, Ref. 1) and the design of key worker shelters (for example, Ref. 2). This work considered the hazards posed by the blast environment and the primary thermal pulse from nuclear weapons. There was, however, very little information on another area of concern — secondary fires. Secondary fires are defined as fires caused by blast or other nonthermal effects of nuclear detonations, in contrast with primary fires, which are a direct result of the thermal radiation of a nuclear weapon. Knowledge of this secondary fire threat is vital to key worker shelter planning and industrial hardening activities.

To answer these concerns Scientific Service, Inc., has been conducting a program to examine the potential for secondary fires in or near structures, with emphasis on critical facilities and industries. This program, which was performed for the Federal Emergency Management Agency under Contract EMW-C-0369 (Work Unit No. 2564I), included the following tasks:

> Using the work of J. McAuliffe and K. Moll (Ref. 3) as a starting point, study the potential for secondary vs primary ignitions by megaton yield nuclear weapons, both surface bursts and air bursts.
>
> Concentrate the analysis on ignitions and secondary fires in critical industries.
>
> Emphasis shall be on the secondary fire effects in the fringe damage areas at approximately 2 to 5 psi peak overpressure, with less emphasis on areas with peak overpressures higher or lower than this range.
>
> The results were to be provided in a form that would assist civil defense planners to understand the potential secondary fire situation in industrial areas following nuclear attack and to devise improved mitigation measures and more effective measures to combat the fires that may be produced.

Report Organization

Section 2 of this report presents a general discussion on primary and secondary ignitions, a review of the Hiroshima and Nagasaki events, and a discussion of ways of reducing the number of secondary ignitions. Section 3 describes the approach used to develop a prediction model, which is presented in Section 4. Three appendixes are included: Appendix A - Earthquakes, Appendix B - Tornadoes and Wind Experience, and Appendix C - Stochastic Secondary Fire Model.

Section 2
GENERAL DISCUSSION

OBJECTIVE AND GENERAL RESULTS

The objective of this program was to expand upon the work of McAuliffe and Moll, Ref. 3, who summarized the state-of-the-art of secondary ignitions in 1965, and to determine if natural disasters that have occurred or research that has been completed in the interim since 1965 have furnished enough new data to change or improve the conclusions presented in Ref. 3. The conclusions in Ref. 3 were essentially as follows: Secondary ignition frequencies were estimated at 0.006 per 1,000 sq ft of total floor area damaged by at least 2 psi blast overpressure; fires during warning and post-attack recovery periods are not potentially critical civil defense problems; however, hazards from such fires, as well as from nuclear- and disaster-caused fires, can be greatly reduced by cutting off electricity and other energy supplies.

The ground rules governing this program were to: study the potential for secondary vs primary ignitions by **megaton** weapons, both surface and air bursts; concentrate on ignitions and secondary fires in **critical** industries; emphasize the **fringe** (2 to 5 psi) areas; and provide the results in a **simple format** that could be readily used by civil defense planners.

The results of the study indicate: in the 2 to 5 psi range, secondary ignitions from **megaton** weapons are probably inconsequential compared with primary ignitions; in the 0.5 to 3 psi range (a vastly larger area than the 2 to 5 psi range), secondary ignitions may prove very important; the principal difference between surface and air bursts lies in the greater ground range at which air bursts cause both mechanical damage and fires (whether primary or secondary); a simply applied fire

prediction model has been developed to enable an assessment of ignitions to be made in any selected industrial area based on type of structure, type of contents, and targeting scenario; the model has been tested with existing data on fire incidents in the normal and in disaster environments. Details are described below.

NUCLEAR WEAPONS AND PRIMARY IGNITIONS

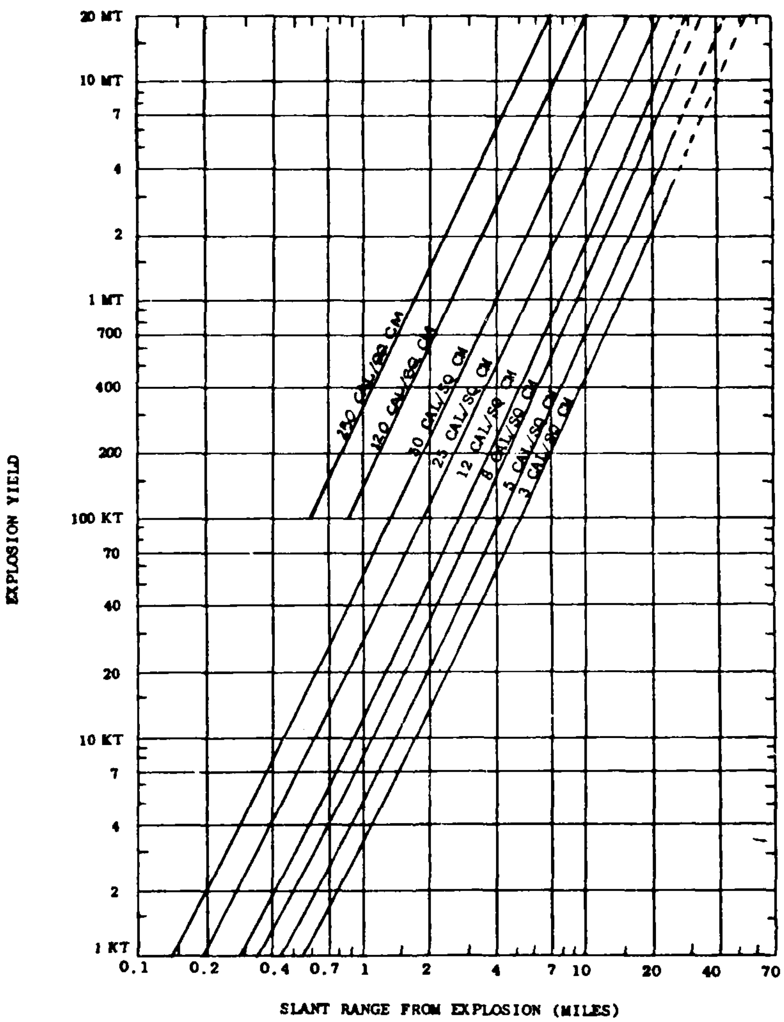
For primary ignitions, the ground range is a function of three factors:

(1) Radiant output (a function of weapon yield and type)
(2) Transmittance (a function of atmospheric conditions)
(3) Target susceptibility (quantity and rate of radiant input to ignite)

Radiant output has been determined from field tests conducted in the range of a few KT to several MT for standard weapons. Data were limited to those tests where height of burst ensured no serious perturbations of the fireball during emission and where transmittance was essentially ideal (50-mile visibility). These data have been translated into the curves of Figure 1, taken from the **Effects of Nuclear Weapons** (Ref 4), to show radiant exposure in calories per square centimeter at the target, as a function of ground range and weapon size. (The curves for radiant exposures of 120 and 250 calories per square centimeter are extrapolations of the Ref. 4 data.) Table 1, taken from the same reference, provides a list of materials and exposures that would be expected to lead to primary ignition as a function of three weapon sizes, and Figure 2 combines ignition exposure for key target materials into graphic form to show dependence on weapon sizes from 1 KT to 100 MT.*

---

* Note that at 27 miles from a 15 MT weapon the radiant exposure is indicated to be 10 to 12 cal/cm^2, enough exposure to cause skin burns at Hiroshima. On Castle Bravo, over a dozen people were exposed to the thermal radiation from a 15 MT weapon at this ground range (on a YAG) without any radiation burns recorded. Thus, rate of thermal input is an important factor.



(Source: Effects of Nuclear Weapons, Table 7.47, page 333; Ref. 4)

Fig. 1. Slant Ranges for Specified Radiant Exposures as a Function of Energy Yield of an Explosion at Moderate Altitude (less than 20 miles) for 50-mile Visibility.

TABLE 1

APPROXIMATE RADIANT EXPOSURE FOR IGNITION OF HOUSEHOLD MATERIALS AND DRY FOREST FUELS*

Material	Weight	Ignition exposure** (cal/sq cm)		
	oz/sq yd	40 kilotons	1 megaton	10 megatons
Newspaper, shredded	2	4	6	11
Newspaper, dark picture area	2	5	7	12
Newspaper, printed text area	2	6	8	15
Paper, crepe (green)	1	6	9	16
Cotton string scrubbing mop, used (gray)#	....	10	15	21
Cotton string mop, weathered (cream)#	....	10	19	26
Matches, paper book, blue head exposed#	....	11	14	20
Excelsior, ponderosa pine (light yellow)#	2 lb/cu ft	(***)	23	23
Paper, Kraft, single sheet (tan)	3	10	13	20
Paper, bristol board, 3 ply (dark)	10	16	20	40
Paper, Kraft, carton, flat side, used (brown)	16	16	20	40
Paper, bond, typing, new (white)#	2	24	30	50
Dry rotted wood punk (fir)#	....	4	6	8
Deciduous leaves (beech)	....	4	6	8
Fine grass (cheat)	....	5	8	10
Coarse grass (sedge)	....	6	9	11
Pine needles, brown (ponderosa)	....	10	16	21

*Certain materials listed in previous editions and printings have been deleted

**The values given are for near sea level detonations of weapons of the yields indicated. Ignition levels (except where marked #) are estimated to be valid within ±25% under standard laboratory conditions. Under typical field conditions the values listed are estimated to be valid within ±50% with a greater likelihood of higher rather than lower values. For materials marked #, ignition levels are estimated to be valid within ±50% under laboratory conditions and within ±100% under field conditions.

***Data not available or appropriate scaling not known.

(Source: Effects of Nuclear Weapons, Table 7.44, page 332; Ref. 4)

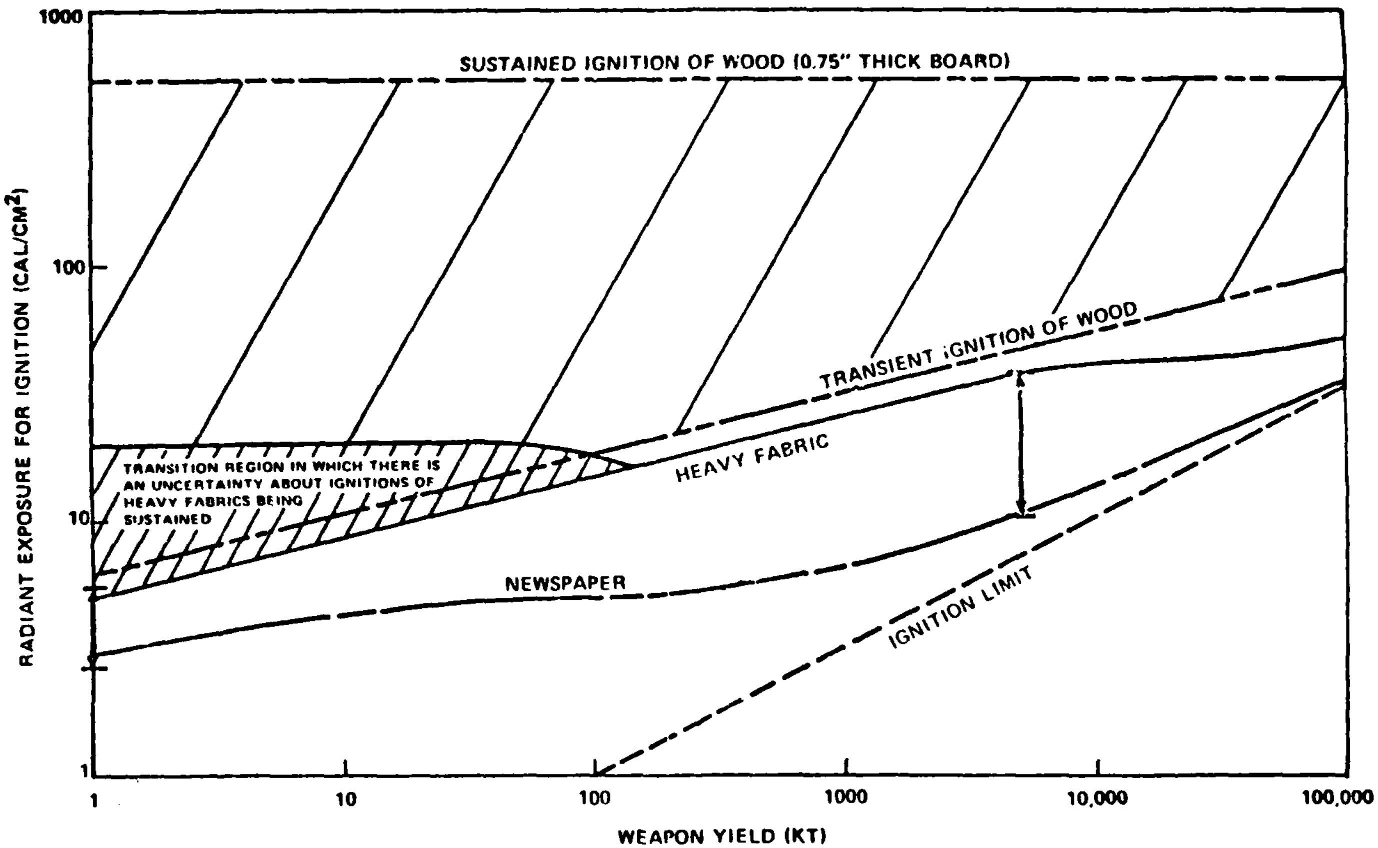


Fig. 2. Radiant Exposures to Ignite Materials (at 40-50% relative humidity) as a Function of Weapon Yield.

Kiloton Weapons

Using Hiroshima experience, where weather was clear and the burst height high enough to correspond to Figure 1 data, these curves should apply. A map in Ref. 5, Vol. III indicates the burnt out area was, roughly, a 6,000 ft radius circle (with several contiguous fingers extending to 10,000 ft) plus a few isolated (non-contiguous) fires outside the 6,000-ft range (Figure 3). The fires were reported to have become a conflagration in a matter of a half an hour with prevailing winds inward toward ground zero because of thermal effects of the coalescing fires. Thus, excepting a small amount of early fire spread, the ring constituting the burnt out area should correspond fairly closely to (but be slightly larger than) the region of primary ignition. This ring had a radius of 1.0 to 1.2 miles so that this range for 12.5 KT (in Figure 1) suggests 8 to 12 cal/cm^2 is sufficient for primary ignition. Table 1 indicates the exposure received there is about one and one-half to two times that necessary weapon to ignite typical materials such as deciduous leaves, dry rotted wood punk, and pine needles, while Figure 2 shows excellent agreement with the 10 cal/cm^2 average received because 9 to 11 cal/cm^2 are required to ignite heavy fabric and wood. Any discrepancy here appears to be within the range of variation inherent in the data and the possible variation in transmittance (Figure 4).

At Nagasaki, where the burst height was also high enough to preclude surface effects, the weather was not quite clear and a reflecting cloud deck lay above the burst. Had the sky been clear, 10 cal/cm^2 should have occurred at about 1.5 miles, or at 7,900 feet, assuming a 22 KT weapon. Nevertheless, a primary ignition was reported at about 12,000 feet (Ref. 5), which corresponds to 3.5 cal/cm^2. If the half of the radiant energy generally lost to the sky were reflected off the cloud deck, perfectly, the 3.5 cal/cm^2 would be doubled. This corresponds fairly well to the expected range for ignition consistent with Figure 1 and radiant energy at the target as observed for the Hiroshima data. For this circumstance primary ignitions overlap the fringe area. Overlap of primary ignition in the fringe area becomes more likely with megaton weapons.

Megaton Weapons

Table 1 indicates roughly 100% greater radiant input is required for primary ignition of listed items when the weapon size is 1 MT versus 20 KT, while Figure 2

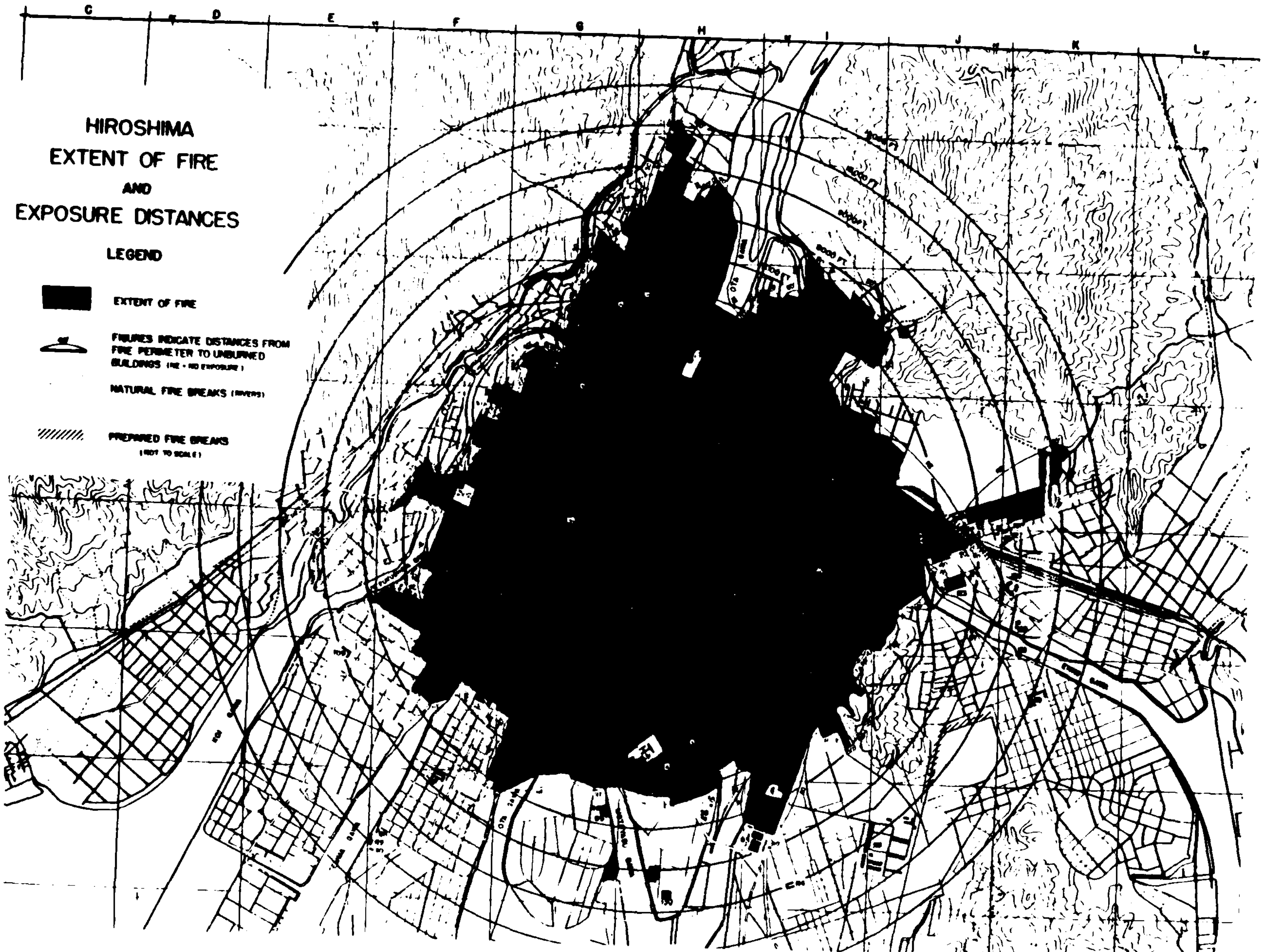
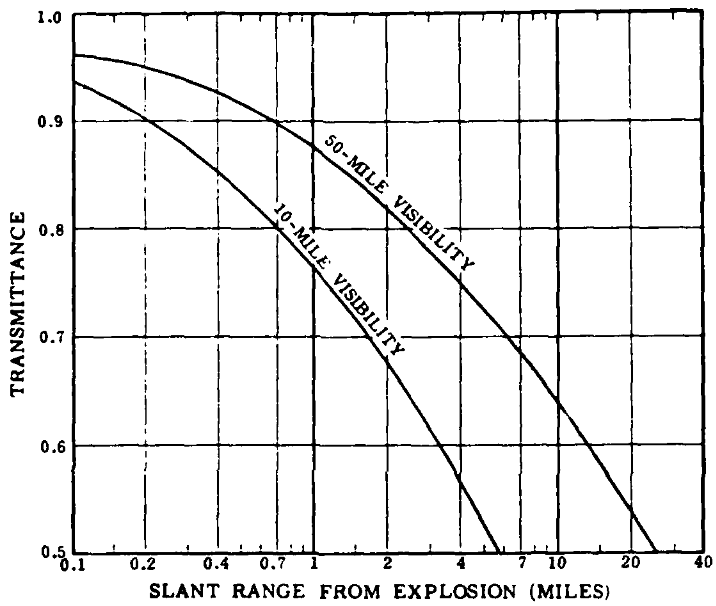


Fig. 3. Map of Hiroshima Damage. *(Source: U.S. Strategic Bombing Survey - Hiroshima, Vol. II; Ref. 5)*



(Source: Effects of Nuclear Weapons, Figure 7.104, page 363; Ref. 4)

Fig. 4. Atmospheric Transmittance as a Function of Distance for Visibilities of 10 miles and 50 miles.

suggests 150% to 200% greater input is required to ignite heavy fabric and wood. For Japanese cities similar to Hiroshima and Nagasaki, where 8 to 12 cal/cm^2 was adequate to ignite primary fires, one might therefore expect 14 to 16 cal/cm^2 would be required had a 1 MT weapon been used. Figure 1 shows the ground range, for an air burst of 1 MT, at which 16 cal/cm^2 would be expected; i.e., about 7.0 miles. From Figure 5 and $W^{1/3}$ scaling, this ground range for primary ignition from an optimum burst height corresponds to 2.3 psi. Optimum heights of burst, however, are probably not very likely. For surface bursts, Ref. 4 suggests a factor of 1.3 to (an average of 1.6) reduction in radiant energy be anticipated, so that to achieve a 16 cal/cm^2 exposure, pick the ground range off Figure 1 where the exposure is 1.6 x 16 cal/cm^2.

For an air burst 10 MT weapon, the exposures, relative to 20 KT, are about four times larger, so that 32 to 50 cal/cm^2 would be expected to cause primary fires at a ground range of 12 to 15 miles where the overpressures are 2.5 to 3.3 psi.

The predicted exposure to radiant energy from a surface burst is a factor of 1.3 to 2.0 less than would be expected from an air burst of the same size (Table 2, taken from Ref. 6). This reduction would correspond to a 10% to 30% reduction in ground range where primary ignitions would be expected. It should be noted, however, that a 50% reduction will also occur in the ground range or distance where the fringe area of from 2 to 5 psi can be expected. Considering the uncertainties in exposure levels to cause primary ignitions and the data required to predict secondary ignitions, the differences to be expected between surface and air bursts is adequately accounted for in the difference between the two pressure-distance falloff curves.

SECONDARY IGNITIONS

Secondary fires are fires that are caused not by the thermal pulse but by blast damage to structures and equipment. Causes of these secondary fires can be:

- Electrical - the shorting of wires that subsequently causes the ignition of nearby materials (the most recent example being the MGM Grand fire, which was caused by a short in an item of

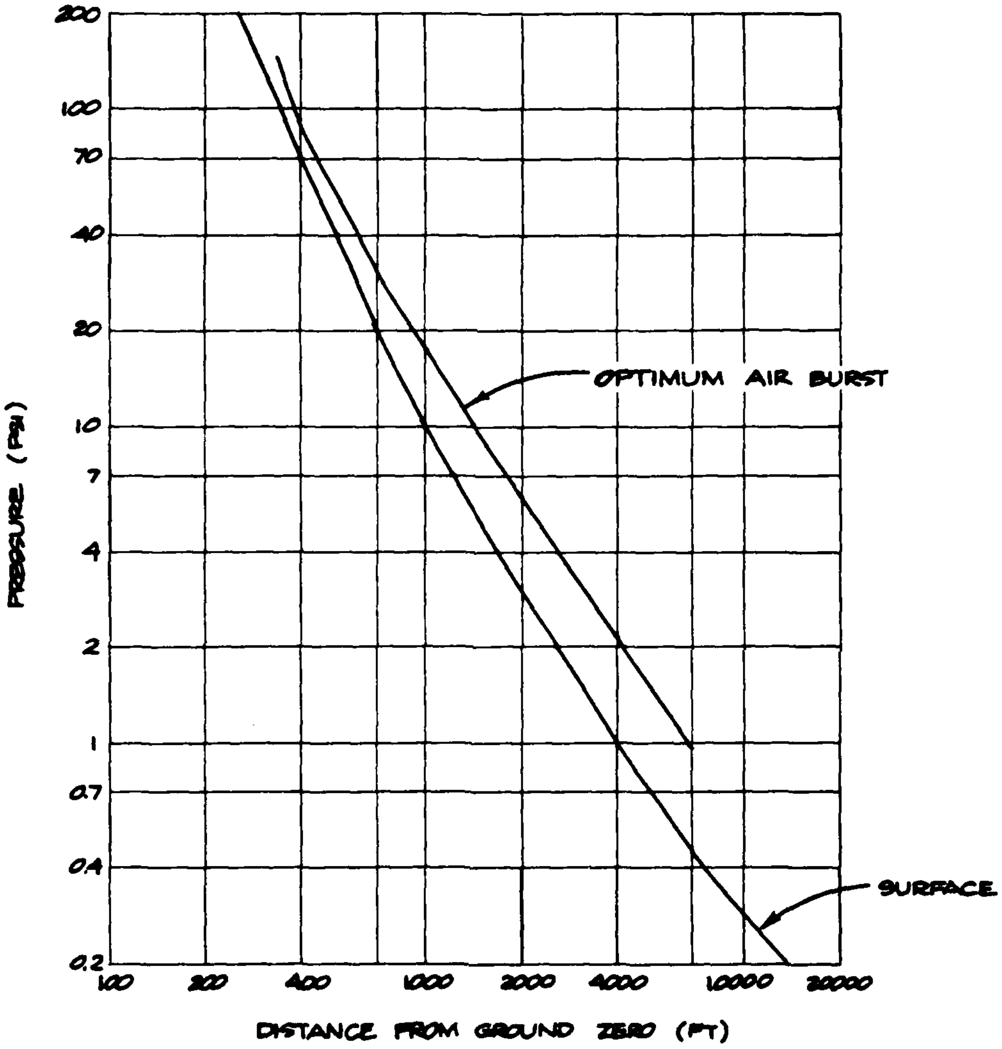


Fig. 5. Peak Overpressure for 1-kiloton Air and Surface Bursts.

TABLE 2

THERMAL RADIATION EXPOSURES (cal cm^{-2})
AT DISTANCES CORRESPONDING TO VARIOUS
AIR BLAST PEAK OVERPRESSURES
(5-MT Explosion; 10-Mile Visibility)

Burst Type	Peak ΔP (psi)	Distance (mi)	Elevation Angle* (deg)		Radiant Exposures (cal cm^{-2}) $\beta = 0$	Radiant Exposures (cal cm^{-2}) $\beta = 5°$
Surface burst	1	12.5	4.0		4.5	0
	2	8.0	6.3		20.7	2.2
	3	6.3	7.9		41.9	10.8
	5	4.7	10.5		90.1	38.2
	10	3.26	15.1		221	131
Airburst						
1 fireball radius height of burst (HOB)	1	14.8	0†	5.4†	3.8	0
	2	9.1	0	8.8	22.7	10
	3	7.1	0	11.4	49.7	26
	5	5.2	0	15.7	114	70
	10	3.55	0	22.8	290	280
2 fireball radii HOB	1	17.0	2.4†	7.1†	2.0	1.0
	2	10.2	4.0	11.8	15.1	14.0
	3	7.8	5.2	15.5	35.4	35.4
	5	5.7	7.2	21	84.2	84.2
	10	3.8	11.0	32	215	215

*Line of sight to top of fireball
†Lines of sight to top and bottom of fireball(s).

(Source: Wiersma and Martin, Evaluation of the Nuclear Fire Threat to Urban Areas. Stanford Research Institute, September 1973; Ref.6)

kitchen equipment damaged by the vibration of a compressor);

- o Thermal - the upsetting of furnace or kiln containing hot heating elements or molten material; flammable materials - the release of gasoline or natural gas through tank or line rupture, which subsequently finds an ignition source;
- o Chemical - the spilling of reactive chemicals, which either ignite by themselves or react with other chemicals or materials;
- o Mechanical - the ignition of flammable materials by the rupture of their containers.

Blast-caused structural failures, impact of flying debris, and redistribution of combustibles and exposed ignition sources in the high velocity winds are the underlying mechanisms for these events.

Blast-caused structural failures are intimately related to both free field static and dynamic overpressures, while the missile and debris velocities in the free field are related principally to the wind velocities. Studies of free field events associated with the latter (e.g., structural failures) have established that long duration flows in the fringe area -- where these velocities range from 110 to 240 ft/s -- can cause considerable damage both from direct effects and from flying debris. Tornado experience confirms this. Therefore, it is worth noting that similar environments to these devastating free field conditions can be created inside unfailing buildings at much lower overpressures. These will occur in unfailing buildings that have openings (windows, cargo access ports, doors) that become (or are) exposed. This can happen at overpressures as low as 0.5 psi through jet action (Ref. 7). Figure 6 is a graph of free field shock and jet velocities as a function of free field static overpressure levels driving the shock. It shows that the jet velocity (u_{jet}) through an opening less than 30% of the loaded area in an unfailing building is 240 ft/s at a free field overpressure of 0.5 psi. Moreover, the figure suggests that closer to ground zero this mechanism may lead to extreme jet velocities inside buildings during the failure process. For example, at the 5 psi ground range (where many concrete structures survived at Hiroshima and Nagasaki) the jet velocities corresponded to Mach 1. This damage mechanism inside non-failing buildings may be particularly important in the fringe area with the long duration flow of large weapons.

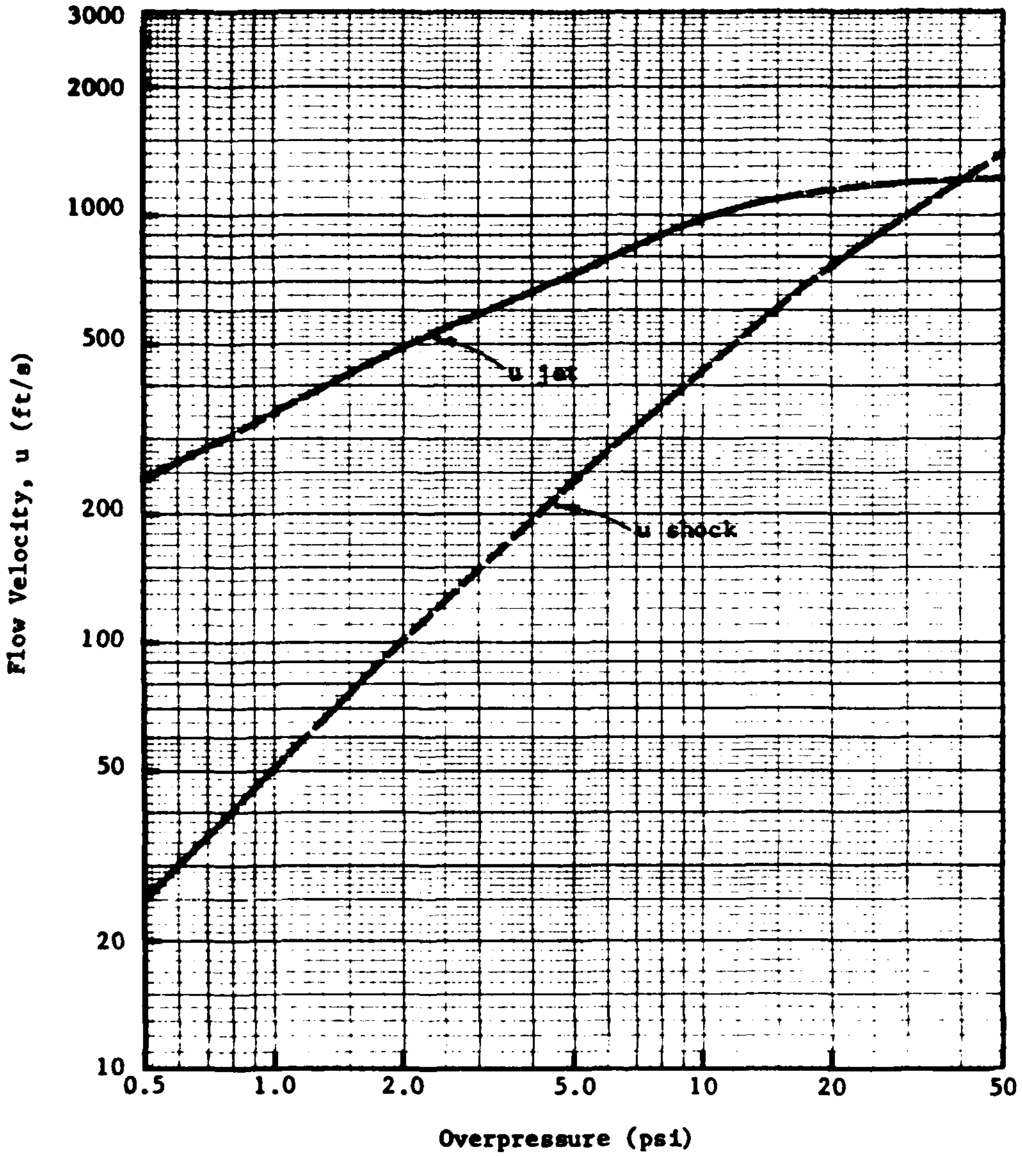


Fig. 6. Jet and Free Field Flow Velocities, u, for Typical Size Openings.

Megaton Weapons and Secondary Ignition

There are very few well documented data on fires initiated by physical damage (i.e., secondary ignitions). Those data available are found in high explosive experience of World War II. Here, the high explosive generated secondary ignitions are scaled using $W^{2/3}$ (Ref. 5). The implication is that the number of ignitions remains fixed per unit area (for a given type of burst) within the threshold range. This threshold range is not specified in the analysis, but the literature on accidental explosions does provide information that a secondary fire has been documented at 2.5 psi (the Texas City disaster). There are at least two difficulties with applying such a simple model. The first is that there is no "a priori" reason to assume a uniform distribution, even though there are no direct data to enable one to do otherwise. If the probability function is dependent on damage (a rational assumption), this parameter is non-uniform and falls off with overpressure (see Appendix C). The second concern is that extrapolation from high explosive data in the 1/4 to 4 ton range takes no cognizance whatever of the jet velocity phenomenon associated with the long duration flow of very large weapons.

Using the high explosive model $W^{2/3}$ normalized to data for 1/4 to 4 ton bombs (Ref. 5), then prediction of secondary fires would run about 84 fires per square mile of building-covered land subjected to 2.5 psi or more. At 5 acres per city block, this is 0.66 fires per block.

A very important question about secondary fires initiated by megaton weapons, however, is at what ground range they become **dominant** for fire ignition and damage. Past experience and inference from nuclear data suggest that primary ignition will be dominant as far out as it occurs, while high explosive data suggest secondary fires are likely to be dominant in the annulus **outside the ground range for primary ignition** but inside the ground range where significant physical damage to buildings and/or contents can occur. Where this outer bound is located relative to the primary ignition range is the key to the importance of secondary ignitions. It seems likely to be in the range of 2 or 3 psi to 0.5 psi.

SECONDARY IGNITION MECHANISMS

Ignition Mechanisms

Major sources for igniting fires that are unrelated to the primary pulse are:

(1) electrical,

(2) thermal,

(3) chemical,

(4) mechanical,

(5) fluid dynamic/electrostatic

The first two of these must be active (i.e., in use) at the time of detonation to be an effective ignition source. Though the third and fourth mechanisms can sometimes be totally activated by whatever force unleashes them, on most occasions these two mechanisms depend on local thermal or electrical sources for the ignition. The fifth ignition source is potentially activated by gas flow in the blast wave to build static charges, either directly from gas flow, or indirectly by swirling and rubbing dust particles together.

It seems likely that many of these ignition mechanisms could be eliminated. The simple act of shutting down electric power and fuel supply lines could change the potential for secondary ignition drastically, because this would leave, principally, the release of extremely reactive (including air- and water-reactive) exothermic chemicals, sparks from friction of metal sliding on metal, concrete, etc., and discharge of static electricity built up by friction processes through high velocity gas flow in jets entering building openings in non-failing buildings. Data from the normal environment on fire ignition, by cause, provide the best measure of the effect to be gained in a blast environment by neutralizing the various ignition mechanisms that can be identified, because in both environments the opportunity for fire will be related to how many of these ignition sources are **live** and so capable of being activated.

Electric Circuits — If the electric power is not cut off at the source the following is likely to occur: at overpressure levels where severe structural damage will occur, electrical systems will be crushed, severed, pierced by collapsing structural members or flying debris to cause shorts; at overpressures where light

damage to structures occurs, electrical appliances and machines may still be overturned and/or wires severed as a result of the overturning or flying debris, also causing shorts; and at lower overpressures, where structures do not fail, overpressure may still collapse electrical enclosures containing circuit breakers, relays, junction boxes, etc., and jets that form at openings of the structure may hurl debris, which can impact and puncture these enclosures.

Of interest to eliminate secondary ignitions is the frequency of electrical fires in the normal (non-blast) environment. In industry, electrical fires accounted for 44% of all reported industrial fires in 1975 in the State of California (Ref. 8). This is taken as a sample large enough to be indicative of the United States. Electrical fires in utilities alone accounted for 16% of the total, or 40% of all electrical fires. Specific data on whether 44% of secondary fires are of electrical origin in a blast environment are non-existent, but might be inferred. Except for differences in blast thresholds that may release different ignition mechanisms, the relative frequency with which ignition sources are likely to be created in a blast environment would be expected to be proportional to the number of sources — just as for the normal environment. Thus, simply turning off electric power at the source, preferably at the power plant, should reduce the number of secondary fires in a blast environment by roughly 44%. Moreover, for those essential industries that must operate though the crisis period, and after, it would be better if they operated from a standby system, hardened onsite, that could be shut off at attack warning. Then, central power plants could be shut down to eliminate the ignitions from long distribution lines severed in the blast.

Thermal Sources. — A thermal source (electric, oil, gas) that operates at a temperature sufficient to ignite wood, paper, cloth, or volatiles is a potential ignition source where structural damage levels range from severe to light. This would occur as a result of bringing a source into contact with combustibles or vice versa. In the normal environment, thermal sources in industry accounted for 24% of all reported industrial fires in 1975 in the State of California. Thus, shutdown of non-essential plants could eliminate a large portion of the secondary fire potential. Critical plants that are essential to keep operating and that cannot shut down in minutes would see many more local thermal ignitions than in the normal

environment. But even this could be controlled with protective housekeeping to preclude opportunities for combustible material to contact the thermal source, or vice versa.

Chemical. — The potential for chemical ignitions stems principally from exothermic reactions initiated by impact or by contact with air, water, or other chemicals on spilling. In addition, there are a variety of chemicals (in great quantities) that can add to the local fuel load when spilled, and which by virtue of being in a liquid or gas phase can migrate rapidly to an otherwise benign ignition source. In the normal environment, chemical sources of fire ignitions in industry accounted for 13% of all reported industrial fires in 1975 in the State of California. It is not recorded what proportion of these were exothermic without benefit of other impetus, but it seems safe to say that the vast majority require contact with an ignition source to develop a fire. Thus, neutralizing electrical and thermal sources should effectively neutralize 95% or more of the chemical ignitions. However, with this potential source, the real concern will be in the post-attack recovery period when crews return, bringing thermal ignition sources along with them among their recovery equipment (hot manifolds, exhaust sparks) and activating others (starting engines, motors, etc.). Hence, reservoirs of spilled chemicals within the fringe areas that were not ignited, for lack of ignition sources, throughout the sheltering period during and following the blast, could suddenly be ignited as a result of recovery operations.

Mechanical. — The potential for mechanical ignition stems from impact-generated sparks that result from rotating machinery bent or misshapen suddenly to rub or scrape, from overturning and sliding equipment along an abrasive surface, from impact of flying debris, from rending of metals. The first type of source can be eliminated by power shutdown and would affect the 19% of fires that occur in the normal environment from operating machinery. The remaining ignition mechanisms of mechanical origin are strictly a product of the blast environment and have no counterpart in the normal environment. Unfortunately, there are no data available on probabilities of occurrence — though it would be fairly straightforward to develop such data, experimentally, that would be pertinent in the fringe zone. It is to be expected that protective housekeeping and industrial hardening activities

would greatly reduce the potential for such ignitions in critical industries in the blast environment, but without more specific experimental data this is difficult to quantify.

Fluid Dynamic/Static Electric. — It is well known that gas flow through an orifice (e.g., in a gas bottle) can leave an insulated container charged with static electricity. On a large scale, dust and water droplets in clouds become charged, as a result of flow processes, to cause lightning. And dust explosions have been triggered by static electricity built up on dust particles in cyclone dust collectors and in enclosed conveyors handling grain. The majority of dust explosion and fire incidents recorded have involved crushing, pulverizing, buffing, grinding, and conveying processes, which can generate static electricity or heat to cause thermal ignition. Whether these mechanisms occur in jet flow with a frequency sufficient to create a significant ignition source would require some experimental studies of the process to determine.

Implications

The major concern for secondary fire will reside in essential industries that must operate in the crisis period; all other plants can shut down, assuming a few days warning, and something in the neighborhood of 99% of the major normal environment ignition sources (smoking, vandalism, etc., not considered) can be deactivated through specific action. It is not expected that the predicted number of fires in the blast environment could be reduced by these actions to 1% of those predicted for no action, because of the hypergolic chemicals, static charge, and frictional spark ignition source characteristics of a blast environment but not of the normal environment. Nevertheless, a factor of 20 to 30 reduction in predicted incidents should apply to these actions for non-operating plants.

For essential industries operating in the crisis period, electrical shutdown at attack warning, and shutoff of all thermal sources (gas, coal, and oil burners) can achieve nearly the same level of mitigation. The exception in such plants will be large thermal reservoirs that cannot cool in minutes, but take hours (molten masses of metal, glass). It will be better if there is a general power shutdown at the power plant, and hardened onsite power systems are used to operate essential industries.

If this is not done, there will be the ignition potential of transmission lines to consider. However, it does not seem reasonable to operate essential industries through a crisis period with no thought of how to operate them post-attack when the transmission lines are down and power plants damaged. Onsite hardened plants are the answer to both problems.

The impact of an across-the-board factor of 30 reduction in secondary ignitions in the fringe area must still be determined. Nearly 70% of the potential damage region lies within the 2 to 5 psi ground range, hence its importance. The key is whether the total number of primary and secondary ignitions can be reduced by mitigation measures to manageable numbers for fire suppression to be effective.

Section 3
APPROACH

The work plan indicated the program would comprise four interrelated tasks:

(1) Updating of natural disaster and fire data;
(2) Development of preliminary prediction model;
(3) Collection and analysis of data to develop prediction parameters;
(4) Testing and evaluation of the prediction model.

Under Task 1, effort was devoted to collecting and analyzing the natural disasters and fires that have occurred since 1965; i.e., since Ref. 3 was published, as well as to a re-analysis of some of the events that were discussed in that reference. As expected, the data available were very limited and of marginal usefulness. Data were collected and are presented in appendices of this report along with discussions of the usefulness of the data to the prediction of secondary fires and comparisons with similar data presented in Ref. 3. The other three tasks are all directly related to the development and evaluation of the model, which is discussed below.

THE BASIC MODEL

After many iterations the basic model is essentially as presented in the work plan and consists of two fundamental index columns, arranged in a nomographic fashion as shown in Figure 7. Values of the building index and contents index are simply joined by a straight line and extrapolated to several other scales that yield an estimate of the number of secondary fires as a function of damage level.

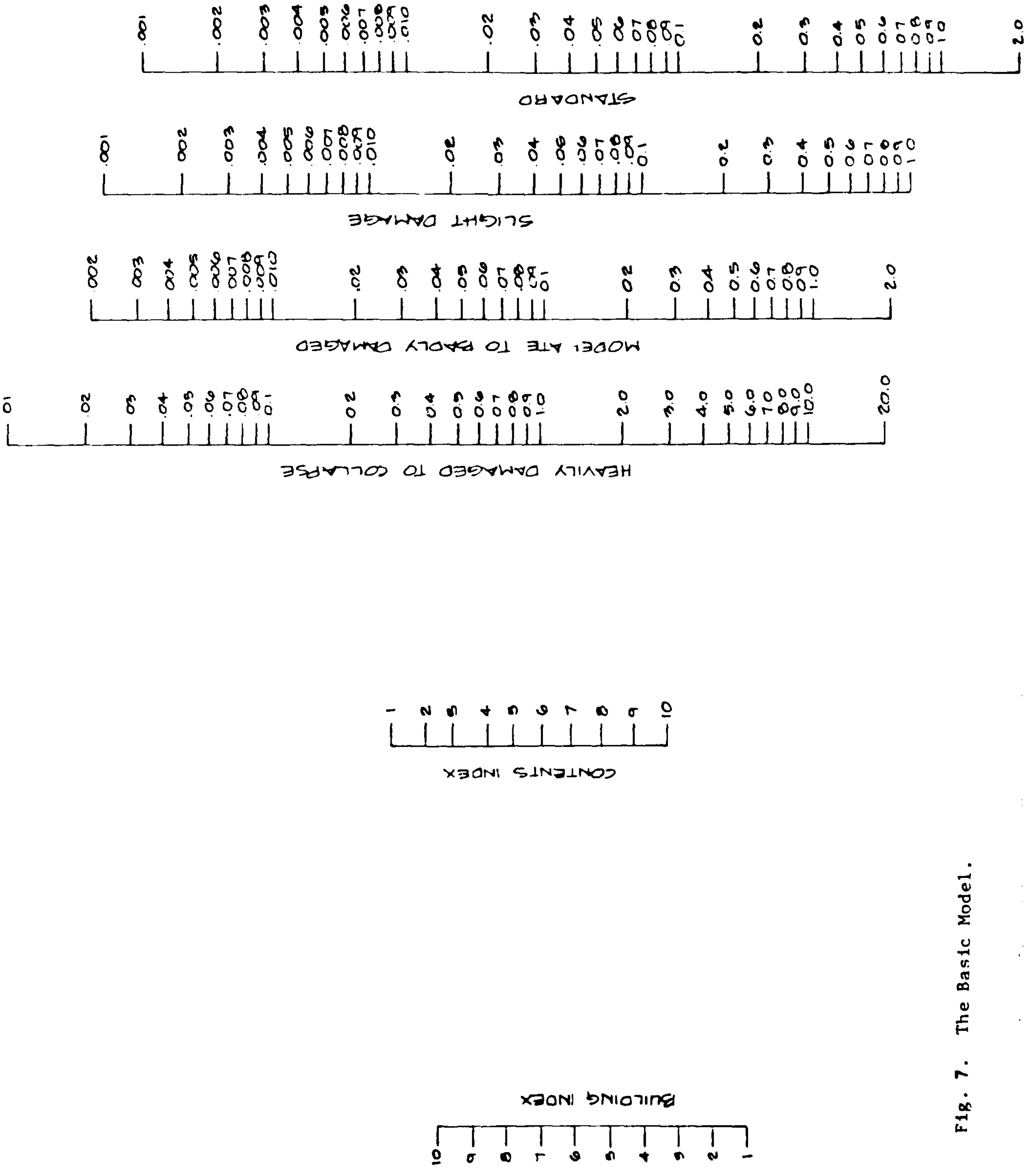


Fig. 7. The Basic Model.

Building Index, (B-1)

The particular values for the building index were obtained using procedures developed by SSI for classification of buildings in host area shelter surveys, Refs. 9 and 10. This process is based on "intended use" code based design criteria. With few exceptions, buildings constructed during the last 50 years were designed using some type of building code, either national or local codes, which are usually adaptations of national codes. The first step is to determine the design criteria used for the structure, which can be expressed as the recommended minimum floor live loads as a function of the original intended use of the structure. A table of minimum floor loads for a variety of common structures is given in Table 3. Thus, if the original intended use and type of construction (i.e., wood, steel, or concrete) are known, it is possible to establish survival loads for the floor system. Based on research conducted at SSI, Refs. 9 through 13, the survival matrix presented in Table 4 was developed. Similar matrices for roofs, Table 5, and walls, Table 6 were also developed from this work. For this study, these data were combined with data from Hiroshima and Nagasaki, nuclear tests in Nevada and the Pacific, large scale blast tests, and natural disaster data to develop the building index presented in Table 7 was developed.

TABLE 3

DESIGN INFORMATION: RECOMMENDED MINIMUM FLOOR LIVE LOADS

UNIFORMLY DISTRIBUTED LOADS

Occupancy or Use	Live Load (psf)
Apartments (*see* Residential)	
Armories and drill rooms	150
Assembly halls and other places of assembly:	
Fixed seats	60
Movable seats	100
Platforms (assembly)	100
Bowling alleys, poolrooms, and similar recreational areas	75
Corridors:	
First floor	100
Other floors, same as occupancy served except as indicated	
Dance halls and ballrooms	100
Dining rooms and restaurants	100
Dwellings (*see* Residential)	
Garages (passenger cars only)	50
Grandstands (*see* Reviewing stands)	
Gymnasiums, main floors and balconies	100
Hospitals:	
Operating rooms, laboratories	60
Private rooms	40
Wards	40
Corridors, above first floor	80
Hotels (*see* Residential)	
Libraries:	
Reading rooms	60
Stack rooms (books & shelving at 65 pcf) but not less than	150
Corridors, above first floor	80
Manufacturing:	
Light	125
Heavy	250

UNIFORMLY DISTRIBUTED LOADS

Occupancy or Use	Live Load (psf)
Office buildings:	
Offices	50
Lobbies	100
Corridors, above first floor	80
File and computer rooms require heavier loads based upon anticipated occupancy	
Penal institutions:	
Cell blocks	40
Corridors	100
Residential:	
Multifamily houses:	
Private apartments	40
Public rooms	100
Corridors	80
Dwellings:	
First floor	40
Second floor and habitable attics	30
Uninhabitable attics	20
Hotels:	
Guest rooms	40
Public rooms	100
Corridors serving public rooms	100
Corridors	80
Reviewing stands and bleachers	100
Schools:	
Classrooms	40
Corridors	80
Sidewalks, vehicular driveways, and yards, subject to trucking	250
Skating rinks	100
Stairs and exitways	100
Storage warehouse:	
Light	125
Heavy	250

UNIFORMLY DISTRIBUTED LOADS

Occupancy or Use	Live Load (psf)
Stores:	
Retail:	
First floor, rooms	100
Upper floors	75
Wholesale	125
Theaters:	
Aisles, corridors, and lobbies	100
Orchestra floors	60
Balconies	60
Stage floors	150
Yards and terraces, pedestrians	100

DESIGN LOAD GROUPS

(as used in this manual)

LIGHT:

40 to 60 psf

MEDIUM:

80 to 125 psf

HEAVY:

150 to 250 psf

TABLE 4: SURVIVAL MATRIX FOR FLOORS

Overpressure at Which 95% of Floors Will Survive "As Built"

Type of Floor Construction and Dead Load	Survival Overpressure (psi)
WOOD D.L. = 20 psf	
Light — Joist, Glulam	1.4
Medium — Joist, Glulam	2.6
Heavy — Plank	3.7
STEEL, LIGHT D.L. = 30 psf	
Light — Open-Web Joist	1.1
Medium — Open-web Joist	2.4
STEEL, HEAVY D.L. = 80 psf	
Light — Beam and Slab	1.0
Medium — Beam and Slab	1.6
Heavy — Beam and Slab	2.7
CONCRETE D.L. = 100 psf	
Light — Single and Double Tees, One-Way Joists	1.4
Light — Hollow-Core Slabs	1.4
Light — One-Way Solid Slabs	1.4
Light — Flat Slab, Flat Plate - Two-Way	1.4
Light — Waffle Slab	1.4

Type of Floor Construction and Dead Load	Survival Overpressure (psi)
CONCRETE D.L. = 100 psf	
Medium — Single and Double Tees, One-Way Joists	2.1
Medium — Hollow-Core Slabs	2.8
Medium — One Way Solid Slabs	2.1
Medium — Flat Slab, Flat Plate Two-Way	2.1
Medium — Waffle Slab	2.1
Heavy — Single and Double Tees, One-Way Joists	3.5
Heavy — Hollow-Core Slabs	5.7
Heavy — One-Way Solid Slabs	6.1
Heavy — Flat Slab, Flat Plate Two-Way	3.5
Heavy — Waffle Slab	3.5

TABLE 5: SURVIVAL MATRIX FOR ROOFS

Overpressure at Which 95% of Roofs Will Survive

Type of Roof Construction and Dead Load	Survival Overpressure (psi)
WOOD D.L. = 15 psf	
Joist, Glulam	0.4
STEEL, LIGHT D.L. = 25 psf	
Open-Web Joist, Plywood Deck	0.3
STEEL, HEAVY D.L. = 60 psf	
Open-Web Joist, Metal Deck	0.4
CONCRETE D.L. = 80 psf	
Single & Double Tees, One-Way Joists	0.8
Hollow-Core Slabs	0.8
One-Way Slabs	0.8
Flat Plate & Flat Slabs	0.8
Waffle Slabs	0.8

TABLE 6: SURVIVAL PRESSURE MATRIX FOR WALLS

Incident Overpressures at which 90% of Walls Will Survive (all tabulated values are in psi)

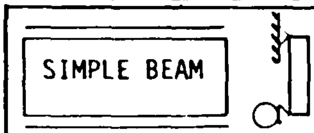
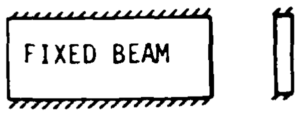
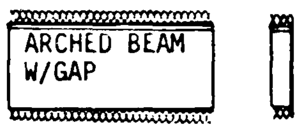
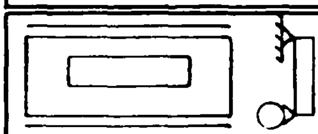
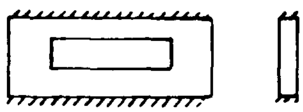
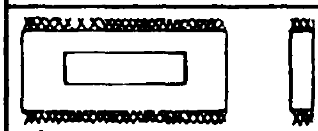
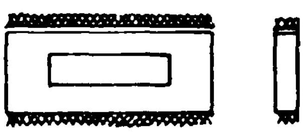
Wall Material and Thickness / Support Condition	Brick			Concrete Block	Composite Concrete Block/ Brick
	4-in.	8-in.	12-in.	8-in.	10-in.
Solid Walls					
 SIMPLE BEAM	0.1	0.4	1.0	0.1	0.7
 FIXED BEAM	0.2	0.7	1.4	0.2	1.0
 ARCHED BEAM	0.8	4.3	7.7	2.6	3.7
 ARCHED BEAM W/GAP	0.2	1.1	1.9	0.6	0.9
Window Walls					
 SIMPLE BEAM	0.2	0.8	1.9	0.4	1.3
 FIXED BEAM	0.4	1.3	2.9	0.5	2.0
 ARCHED BEAM	0.8	5.3	9.8	3.2	4.5
 ARCHED BEAM W/GAP	0.3	0.6	2.5	0.8	1.3

TABLE 6: SURVIVAL PRESSURE MATRIX FOR WALLS (contd)

Incident Overpressures at which 90% of Walls Will Survive (all tabulated values are in psi)

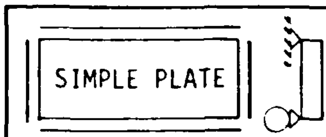
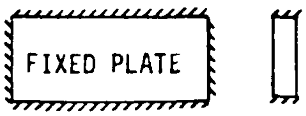
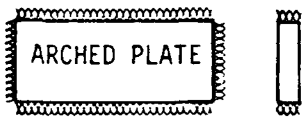
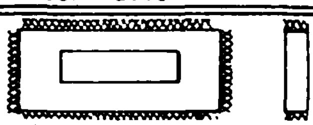
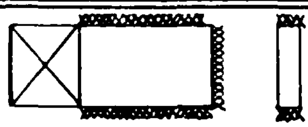
Wall Material and Thickness / Support Conditions	Brick			Concrete Block	Composite Concrete Block/ Brick
	4-in.	8-in.	12-in.	8-in.	10-in.
PLATES					
Solid Walls					
 SIMPLE PLATE	0.2	0.7	1.6	0.3	1.1
 FIXED PLATE	0.4	1.5	3.4	0.6	2.3
 ARCHED PLATE	1.5	7.7	13.3	2.6	3.7
Window Walls					
 ARCHED PLATE	1.8	9.3	17.1	3.2	4.5
Doorway Walls					
 ARCHED PLATE	1.8	9.2	16.8	4.6	6.7

TABLE 6: SURVIVAL PRESSURE MATRIX FOR WALLS (contd)

Incident Overpressures at which 90% of Walls Will Survive (all tabulated values are in psi)

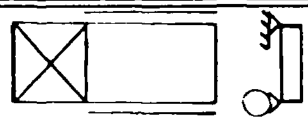
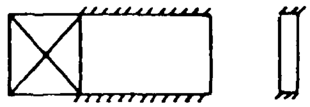
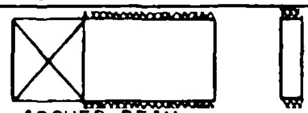
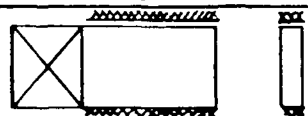
Wall Material and Thickness / Support Conditions	Brick			Concrete Block	Composite Concrete Block/ Brick
	4-in.	8-in.	12-in.	8-in.	10-in.
Doorway Walls					
 SIMPLE BEAM	0.2	0.7	1.5	0.3	1.0
 FIXED BEAM	0.3	0.4	2.3	0.5	1.6
 ARCHED BEAM	1.5	7.7	14.0	4.6	6.7
 ARCHED BEAM W/GAP	0.4	2.0	3.5	1.2	1.7

TABLE 7: BUILDING INDEX

1. **Heavy Design**
   Reinforced concrete structures designed for protective purposes (e.g., bank vaults, nuclear containment vessels and control rooms)

2. **Heavy Design**
   Reinforced concrete walls, roofs, and floors or heavy steel frame, metal deck supported by steel purling, with reinforced concrete topping; walls of concrete block or brick (e.g., heavy manufacturing, power plants, storage warehouses)

3. **Heavy Design**
   Reinforced concrete frame with precast concrete walls, floors, and roof; or heavy timber frame with heavy timber floor and walls of concrete block or brick (r.g., heavy manufacturing, office buildings, warehouses)

4. **Medium Design**
   Precast concrete frame with precast walls, floors, and roof, or heavy timber frame with medium loading floors and walls of concrete block or brick, or medium design reinforced concrete walls, floors, and roof (e.g., light manufacturing, large retail or wholesale stores)

5. **Medium Design Load**
   Concrete block or brick wall, precast concrete floors/roof, with wall openings of more than 10% (light manufacturing, retail and wholesale stores, light storage warehouses)

6. **Medium Design Load**
   Concrete block or brick walls, precast concrete roofs/floors with less than 15% wall openings; precast concrete walls with precast concrete floors and roofs (pumphouses, mechanical equipment buildings, storage buildings, water and sewage treatment plants, light manufacturing)

7. **Light Design Load**
   Concrete block or brick walls, timber roofs and floors with more than 15% openings in walls (retail stores, motels, professional buildings, office buildings)

8. **Light Design Load**
   Concrete block or brick walls, timber roofs and floors with less than 15% wall opening (mini warehouses, construction storage buildings)

9. **Light Design**
   Precast concrete walls with timber joist roofs and floors or steel joist roof and floors; light steel frame, infill walls with steel joists and roofs (warehouses, office buildings, and light manufacturing)

10. **Light Design**
    Wood/metal stud walls, with siding, stucco, brick veneer; timber joist or glulam roofs and floors; light corrugated metal walls and roofs (residences, restaurants, small retail stores, storage sheds, light manufacturing)

Contents Index (C-1)

There are many indices commonly used by building codes, insurance companies, and associations, such as the National Fire Protection Association, for the classification of occupancies and contents of structures. One of the more useful with regard to combustibility of contents is used by the Insurance Services Office in their publication Commercial Fire Rating Schedule (Ref. 14). These combustibility classifications are as follows:

> Class 1 - Non-Combustible: Merchandise, materials, or equipment that in permissible quantities do not in themselves constitute an active fuel for the spread of fire. The maximum amount of combustible materials in any 10,000 sq ft of an occupancy otherwise containing non-combustible materials, shall not exceed 1,000 bd ft of lumber or over two barrels (110 gallons) of combustible liquids or greases, or equivalent amounts of combustible materials. The maximum total area containing combustible material in any occupancy otherwise containing non-combustible materials, shall not exceed 5% of the total area of the structure. For purposes of determining this classification, combustible interior walls or partitions, mezzanines, racks, shelves, bins and similar combustible construction shall be considered combustible material. Occupancies usually eligible for a C-1 rating are asbestos, clay or glass, stone or metal products, and metalworking machinery.

> Class 2 - Limited Combustibility: Merchandise or materials including furniture, stock or equipment of low combustibility with a limited concentration of combustible materials (e.g., in hospitals).

> Class 3 - Combustible: Merchandise or materials including furniture, stock, or equipment of moderate combustibility (e.g., in food markets, hardware, and appliance stores).

Class 4 - Free Burning: Merchandise or materials including furniture, stock or equipment that burn freely (e.g., natural fibers, furniture, and wood products).

Class 5 - Rapid burning or flash burning: Merchandise or materials that either burn with great intensity or spontaneously ignite, or give off flammable or explosive vapors at ordinary temperatures or as a result of industrial processes, produce large quantities of dust (coal dust, wheat dust) or other finely divided debris subject to flash fire or explosion. Examples include ammunition, explosives, mattress manufacturing.

In Ref. 14 the various occupancies are listed (abrasives, advertising agencies, etc.) and assigned a "C" number from one to five, which is used for fire insurance rating purposes. Other sources of data useful for the evaluation of building contents and occupancies are the fire experience data from the National Fire Data Center, the State of California Fire Incident Reporting System, and insurance company rating schedules and experience data. An analysis of these data sources was performed during this program and is summarized in Table 8. This table ranks typical occupancies into ten groups, with each group being more hazardous than the previous one; i.e., Group 1 being the least hazardous and Group 10 the most hazardous. Also the occupancies within each group are ranked in order of increasing hazard.

The data from all these sources have been analyzed and refined to produce the occupancy/contents index presented in Table 9. The format of this list is patterned after the Fire Incident Reporting System and is arranged by type of occupancy to make it easier to use by civil defense planners. As the major interest in this program was critical industries and facilities, the list was designed to evaluate, with the exceptions noted below, only those industries considered to be critical for support of crisis relocation, national defense, and immediate post-attack recovery. The selection was based on available data from past research efforts — for example, Refs. 15 through 17 (a typical list, from Ref. 15, is shown in Table 10) — and from recent crisis relocation planning projects conducted at SSI. Table 9

TABLE 8: RANKING BASED ON FIRE EXPERIENCE

Group 1 - Least Hazardous

- 1.1 Quarry and ground pit operations
- 1.2 Water system facilities
- 1.3 Sewage system facilities, pumping plants
- 1.4 Nonferrous metals, refining, and foundries
- 1.5 Steel smelting, foundries, and forge shops
- 1.6 Heavy electrical equipment manufacturing
- 1.7 Electrical power generation plants
- 1.8 Electrical equipment manufacturing
- 1.9 Punch press and steel stamping plants

Group 2

- 2.0 Gypsum wallboard manufacturing
- 2.1 Creameries, ice cream manufacturing
- 2.2 Canneries
- 2.3 Paper manufacturing, heavy
- 2.4 Truck, bus, and railroad equipment manufacturing
- 2.5 Railroad shops and yards
- 2.6 Bakeries, bread production
- 2.7 Offices, including banks
- 2.8 Glass, flat plate manufacturing
- 2.9 Engine, pump, and turbine manufacturing

Group 3

- 3.0 Convalescent homes
- 3.1 Hospitals
- 3.2 Colleges and universities
- 3.3 Primary and secondary schools
- 3.4 Produce, food processing
- 3.5 Glass container manufacturing
- 3.6 Libraries
- 3.7 Electrical hardware manufacturing
- 3.8 Electric power substations
- 3.9 Churches and church schools

Group 4

- 4.0 Communications equipment (telephone) manufacturing
- 4.1 Custom machine shops
- 4.2 Metal fabrication, welding shops
- 4.3 Farming, field crops, poultry and eggs
- 4.4 Heavy construction equipment manufacturing
- 4.5 Meat packing including slaughtering
- 4.6 Electronics equipment manufacturing
- 4.7 Ship terminal facilities
- 4.8 Rapid transit facilities
- 4.9 Shipyards

Group 5

- 5.0 Radio and television stations
- 5.1 Computer installations
- 5.2 Hotels, motels (not high rise)
- 5.3 Warehouses and distribution centers
- 5.4 Textile and garment manufacturing
- 5.5 Production printing plants
- 5.6 Bakeries with donut making
- 5.7 Candy manufacturing
- 5.8 Ranching, cattle and other livestock
- 5.9 Aircraft hangars

Group 6

- 6.0 Paper, box and carton manufacturing
- 6.1 Record storage
- 6.2 Retail stores
- 6.3 Meat products, preparation and packaging
- 6.4 Vegetable oil processing
- 6.5 Dairy farms
- 6.6 Poultry products processing
- 6.7 High speed machining and screw machines
- 6.8 Textile mills using cotton and synthetics
- 6.9 Printing, job shops

Group 7

- 7.0 Coal mine facilities
- 7.1 General storage warehouses
- 7.2 Railroad freight terminals
- 7.3 Truck line facilities, including shops
- 7.4 Truck freight terminals
- 7.5 High rise hotels, apartments, and offices
- 7.6 Aircraft manufacturing
- 7.7 Marine storage facilities, yards and shops
- 7.8 Aircraft maintenance
- 7.9 Busline facilities, including shops

Group 8

- 8.0 Radio and television transmitters
- 8.1 Electronic semiconductor manufacturing
- 8.2 Automotive shops and service stations
- 8.3 Sanitation, and trash handling facilities
- 8.4 Mobile home manufacturing
- 8.5 Woodworking and furniture factories
- 8.6 Sawmills
- 8.7 Lard, tallow, etc., rendering plants
- 8.8 Coated paper and plastic laminate manufacturing
- 8.9 Asphalt plants

Group 9

- 9.0 Auto body shops
- 9.1 Fiberglass boat manufacturing
- 9.2 Paint manufacturing, including storage
- 9.3 Plastic products, including foams, manufacturing
- 9.4 Coal gasification plants
- 9.5 Grain storage elevators
- 9.6 Hazardous (combustible or flammable) chemicals manufacturing
- 9.7 Petroleum refineries
- 9.8 Ordnance manufacturing
- 9.9 Explosives and pyrotechnics manufacturing

Group 10 - Most Hazardous

- 10 Autoignition materials handling facilities

TABLE 9: CONTENTS INDEX

Agriculture/Food
- Bakeries, bread producing – 2.6
- Bakeries, with donut production – 5.6
- Candy manufacturing – 5.7
- Canneries – 2.2
- Creameries, ice cream manufacture – 2.1
- Dairy farms – 6.5
- Farming, field crops, poultry, and eggs – 4.3
- Lard, tallow, etc., rendering plants – 8.7
- Meat packing, including slaughtering – 4.5
- Meat products, preparation and packaging – 6.3
- Poultry products processing – 6.6
- Produce, food processing – 3.4
- Ranching, cattle and other livestock – 5.8
- Vegetable oil processing – 6.4

Chemicals and Plastics Manufacturing
- Fiberglass boat manufacturing – 9.1
- Hazardous (combustible or flammable) chemicals –9.6
- Paint manufacturing, including storage – 9.2
- Plastic products, including foams, manufacture – 9.3

Communications Facilities
- Fire, police communication facilities – 5.0
- Radio and television stations – 5.0
- Radio and television transmitters – 8.0

Electrical Equipment Manufacturing
- Electrical hardware manufacturing – 3.7
- Electrical equipment manufacturing – 1.8
- Heavy electrical equipment manufacturing 1.6

Electronic Equipment Manufacturing
- Communications equipment (telephone) – 4.0
- Electronics equipment manufacturing – 4.6
- Electronic semiconductor manufacturing – 8.1

Fuels
- Coal gasification plants – 9.4
- Petroleum refineries – 9.7
- Service stations – 8.2

Foundries and Machine Shops
- Custom machine shops – 4.1
- High speed machining and screw machines – 6.7
- Metal fabrication, welding shops – 4.2
- Nonferrous metals, refining and foundries – 1.4
- Punch press and steel stamping plants – 1.9
- Steel smelting, foundries and forge shops – 1.5

Glass/Ceramic Manufacturing
- Glass container manufacturing – 3.5
- Glass, flat plate manufacturing – 2.8

Medical Facilities
- Convalescent homes – 3.0
- Hospitals – 3.1

Mining and Quarries
- Coal mine facilities – 7.0
- Quarry and ground pit operations – 1.1

Offices, Schools, etc.
- Churches and church schools – 3.9
- Colleges and universities – 3.2

Offices, Schools, etc. (contd)
- High rise hotels, apartments, and offices – 7.5
- Hotels, motels (not high rise) – 5.2
- Libraries – 3.6
- Offices, including banks – 2.7
- Primary and secondary schools – 3.3

Paper Manufacturing
- Coated paper and plastic laminate manufacturing – 8.8
- Paper, box and carton manufacturing – 6.0
- Paper manufacturing, heavy – 2.3

Printing Facilities
- Printing, job shops – 6.9
- Production printing plants –5.5

Storage Facilities
- General storage warehouses – 7.1
- Marine storage facilities, yards and shops – 7.7
- Record storage – 6.1
- Warehouses and distribution centers – 5.3

Textile Manufacturing
- Textile and garment manufacturing – 5.4
- Textile mills using cotton and synthetics – 6.8

Transportation Facilities
- Aircraft hangars – 5.9
- Busline facilities, including shops – 7.9
- Rapid transit facilities – 4.8
- Railroad freight terminals – 7.2
- Railroad shops and yards – 2.5
- Ship terminal facilities – 4.7
- Shipyards – 4.9
- Truck freight terminals – 7.4
- Truckline facilities, including shops – 7.3

Utilities
- Electric power generation plants – 1.7
- Electric power substations – 3.8
- Sewage system facilities, pumping plants – 1.3
- Water system facilities – 1.2

Vehicle manufacturing and service
- Aircraft maintenance shops – 7.8
- Aircraft manufacturing – 7.6
- Auto body shops – 9.0
- Automotive repair shops – 8.2
- Engine, pump, and turbine manufacturing – 2.9
- Mobile home manufacturing – 8.4
- Truck, bus and railroad equipment manufacturing – 2.4

Wood Products Manufacture
- Woodworking and furniture factories – 8.5
- Sawmills – 8.6

Miscellaneous
- Asphalt plants – 8.9
- Autoignition materials handling facilities – 10
- Computer installations – 5.1
- Explosives and pyrotechnics manufacturing – 9.9
- Gypsum wallboard manufacturing – 2.0
- Ordnance manufacturing – 9.8
- Retail stores – 6.2

TABLE 10: CRITICAL INDUSTRIES

Industry	SIC
Cash grain (feed)	0113
Cash grain farms	0113
Sugarbeet farms	0119
Field crops	012
Vegetable farms	0123
Livestock farms	013
Dairying	0132
Oil & gas extraction	1311
Heavy const. contractors	162
Pipeline contractors	1621
Food	20
Lard (meat packing)	2011-3
Eggs, frozen, etc.	2015
Grain mills	2041
Feed mills	2042
Cereal preparations	2043
Rice mills	2044
Blended & flour	2045
Wet corn milling	2046
Bread bakeries	2051
Cane sugar mills	2061-2
Beet sugar mills	2063
Cottonseed oil mills	2091
Soybean oil mills	2092
Snortening, oils	2096
Yeast	2099
Paper mills	262
Coated paper	2641
Paperboard boxes	265
Printing & publishing	275
Industrial chemicals	281
Plastics	282
Drugs	283
Agricultural chemicals	287
Pesticides	2879
Salt	2899
Petroleum refining	291
Tires & tubes	301
Flat glass	321
Cement, hydraulic	3241

Industry	SIC
Concrete, gypsum, plastics	327
Blast furnaces, steel	331
Iron, steel foundries	332
Nonferrous refining	333
Nonferrous (secondary)	334
Rolling, nonferrous	335
Nonferrous foundries	336
Misc. primary metals	339
Metal containers	3411
Fabricated structural metals	344
Screw machine products	345
Engines & turbines	351
Const. & related machinery	353
Metal working machines	354
Gen. industrial machinery	356
Office machines	357
Elec. distribution products	361
Elec. industrial apparatus	362
Communications equipment	366
Electronic components	367
Aircraft & parts	372
Ships & boats	373
Railroad equipment	374
Instruments	382
Railroads	401
Local & suburban transit	41
Trucking, motor	421
Water transportation	44
Crude oil pipelines	4612
Oil product pipelines	4613
Telephone systems	4811
Electric co's & systems	4911
Gas co's & systems	492
Natural gas pipelines	4922
Water supply systems	4941
Sewerage systems	4952
Lumber wholesalers	5098
Lumber retailers	5211
Elem. & secondary schools	8211

includes a wide variety of industries and support facilities, many of which do do appear on any other currently available essential or critical industry list. Factors contributing to the particular composition of this list were:

- o Concern for damage from surroundings -- While most industrial and manufacturing facilities are not susceptible to primary and secondary fires, they are vulnerable to fire spread. Thus, the neighborhood should be carefully checked, since the structures in the immediate vicinity can have a large effect on the number of secondary fires in a given facility because of debris or highly flammable materials that spread from nearby structures (a good example is an Oakland, CA, foundry that is surrounded by a gasoline tank farm);
- o Lack of sufficient research identifying all the support industries that are critical;
- o Recent studies identifying numerous facilities that will be critical to crisis relocation.

STRUCTURAL DAMAGE INDICES

The focus of this study of the prediction of secondary fires is critical industries and facilities. This is for the most part the industrial manufacturing segment of our nation. In general, industrial buildings have large open floor areas with few intervening walls and compartments and are low in height; i.e., in the one or two story category. They also tend to be functional, of relatively light construction (as opposed to monumental blast-resistant type of construction), and are typically well engineered.

One of the major tasks of this program was to establish failure criteria for the various types of structures listed in Table 7, and to determine overpressure levels at which light, medium, and heavy damage would occur. It was also necessary to define what was meant by light, medium, and heavy damage in the context of secondary fire prediction. The criteria established for use in this program were as follows:

Light Damage - Some roof and wall damage; most windows and doors removed; minor or no damage to the interior contents.

Medium Damage - All windows and doors removed; partial collapse of roof, walls, and floors; significant contents damage.

Heavy Damage - Collapse of roof, walls, and floors; damage to 90% of the contents.

To determine the overpressure levels at which these damage levels would occur an analysis was made of: The Hiroshima and Nagasaki experience; the results of the nuclear weapon tests in Nevada and the Pacific (a summary of these data is shown in Table 11, from Ref. 4); the data from large yield high explosive tests; and the damage caused by earthquakes and other natural disasters. The best source of data, however, was the SSI shock tunnel data and the results of recent programs conducted for the Federal Emergency Management Agency by SSI in support of the host area and key worker area shelter upgrading programs, Refs. 9 through 13. The survival data from some of these programs was presented earlier in Tables 4 through 6. Typical failure data; i.e., 95% probability of collapse overpressures, are presented in Tables 12 through 14.

Many of the industrial buildings in the western portion of the United States are tilt-up structures. The walls of these structures are generally poured onsite on the ground and, when cured, tilted up and moved into place. The roof system, which helps tie the structure together, is usually wood, composed of glulam beams with plywood decking and tar and gravel covering. A typical example is the SSI main office and laboratory, shown in Figure 8A. In the Midwest these structures are more likely to have a steel joist type of roof framing system, which includes lightweight concrete on steel decking. A sketch of this type of construction is shown in Figure 8B. Both of these roof systems are closely designed to local code requirements and weather conditions and seldom exceed a design load of 30 lb per sq ft. With this kind of design load, failures of these roof systems would be expected at the 0.5 to 1 psi range, which suggests that there would be a significant amount of building collapse of these tilt-up buildings at as low as 0.5 psi overpressure.

TABLE 11

DAMAGE RANGES FOR 1-MT TYPICAL AIR BURST

Peak Wind Velocity (mph)	Positive Phase Duration (sec)	Peak Dynamic Pressure (psi)	Peak Over-Pressure (psi)	Range from Ground Zero (Miles)	Range from Ground Zero (1000 FT)	Damage
				10		Light damage to window frames and doors, moderate plaster damage out to about 15 miles, glass breakage possible out to 30 miles.
44	3.45	0.036	1.2		50	
				9		
51	3.45	0.049	1.4		45	Fine kindling fuels ignited.
				8		
60	3.44	0.072	1.7		40	
				7		Smokestacks: slight damage.
72	3.43	0.11	2.1		35	
				6		Wood-frame buildings: moderate damage
89	3.40	0.16	2.6		30	Radio and TV transmitting towers: moderate damage
				5		Wood-frame buildings: severe damage Telephone & power lines: limit of significant damage.
117	3.24	0.28	3.5		25	Wall-bearing, brick buildings (apartment house type): moderate damage
				4		Wall-bearing, brick buildings (apartment house type): severe damage
177	3.02	0.60	5.5		20	Light steel-frame, industrial buildings: moderate damage Light steel-frame, industrial buildings: severe damage Multistory, wall-bearing buildings (monumental type): moderate damage
				3		
278	2.69	1.40	9.4		15	Multistory, wall-bearing buildings (monumental type): severe damage Highway and RR truss bridges: moderate damage. Multistory, steel-frame building (office type): severe damage. Transportation vehicles: moderate damage
				2		
464	2.25	5.22	18.0		10	Multistory, reinforced-concrete frame buildings (office type): severe damage
				1		Multistory, blast-resistant designed, reinforced-concrete buildings: moderate
307	1.75	3.60	27.0		5	Multistory, blast-resistant designed, reinforced-concrete buildings: severe. All other (above ground) structures: severely damaged or destroyed.
				0	0	Ground zero for 1 MT air burst

(Source: <u>Effects of Nuclear Weapons</u>, Table 12.22b, page 640; Ref. 4)

TABLE 12: FAILURE MATRIX FOR FLOORS

Overpressure at Which 95% of Floors Will Fail

Type of Floor Construction and Dead Load	Failure Overpressure (psi)
WOOD D.L. = 20 psf	
Light — Joist, Glulam	2.2
Medium — Joist, Glulam	4.2
Heavy — Plank	5.9
STEEL, LIGHT D.L. = 30 psf	
Light — Open-Web Joist	1.4
Medium — Open-web Joist	3.1
STEEL, HEAVY D.L. = 80 psf	
Light — Beam and Slab	1.3
Medium — Beam and Slab	2.1
Heavy — Beam and Slab	3.5
CONCRETE D.L. = 100 psf	
Light — Single and Double Tees, One-Way Joists	2.0
Light — Hollow-Core Slabs	2.0
Light — One-Way Solid Slabs	2.0
Light — Flat Slab, Flat Plate - Two-Way	2.0
Light — Waffle Slab	2.0

Type of Floor Construction and Dead Load	Failure Overpressure (psi)
CONCRETE D.L. = 100 psf	
Medium — Single and Double Tees, One-Way Joists	2.9
Medium — Hollow-Core Slabs	3.9
Medium — One Way Solid Slabs	2.9
Medium — Flat Slab, Flat Plate Two-Way	2.9
Medium — Waffle Slab	2.9
Heavy — Single and Double Tees, One-Way Joists	4.9
Heavy — Hollow-Core Slabs	8.0
Heavy — One-Way Solid Slabs	8.5
Heavy — Flat Slab, Flat Plate Two-Way	4.9
Heavy — Waffle Slab	4.9

TABLE 13: FAILURE MATRIX FOR ROOFS

Overpressure at Which 95% of Roofs Will Survive

Type of Roof Construction and Dead Load	Failure Overpressure (psi)
WOOD D.L. = 15 psf	
Joist, Glulam	0.6
STEEL, LIGHT D.L. = 25 psf	
Open-Web Joist, Plywood Deck	0.4
STEEL, HEAVY D.L. = 60 psf	
Open-Web Joist, Metal Deck	0.5
CONCRETE D.L. = 80 psf	
Single & Double Tees, One-Way Joists	1.1
Hollow-Core Slabs	1.1
One-Way Slabs	1.1
Flat Plate & Flat Slabs	1.1
Waffle Slabs	1.1

TABLE 14: FAILURE MATRIX FOR WALLS

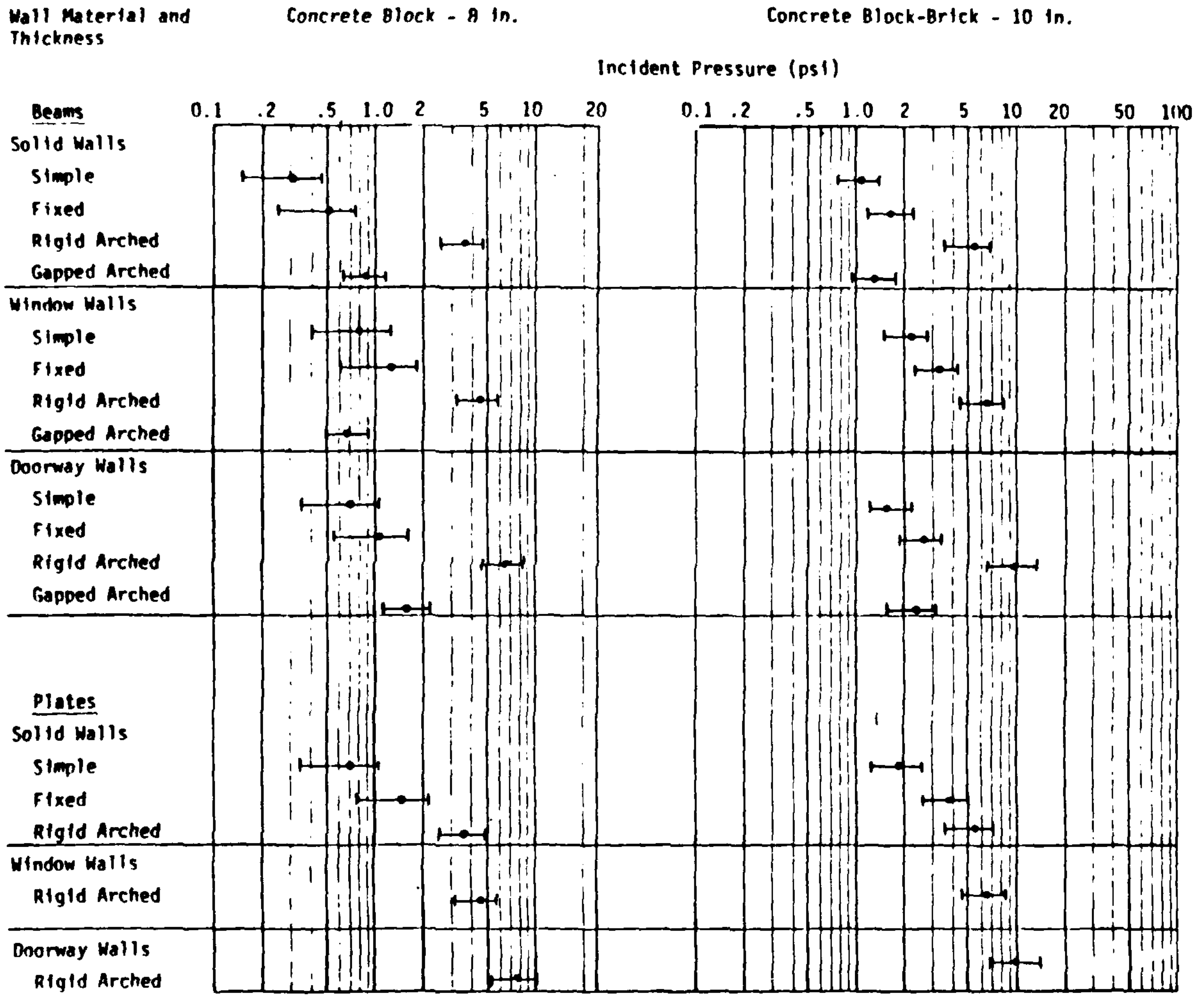
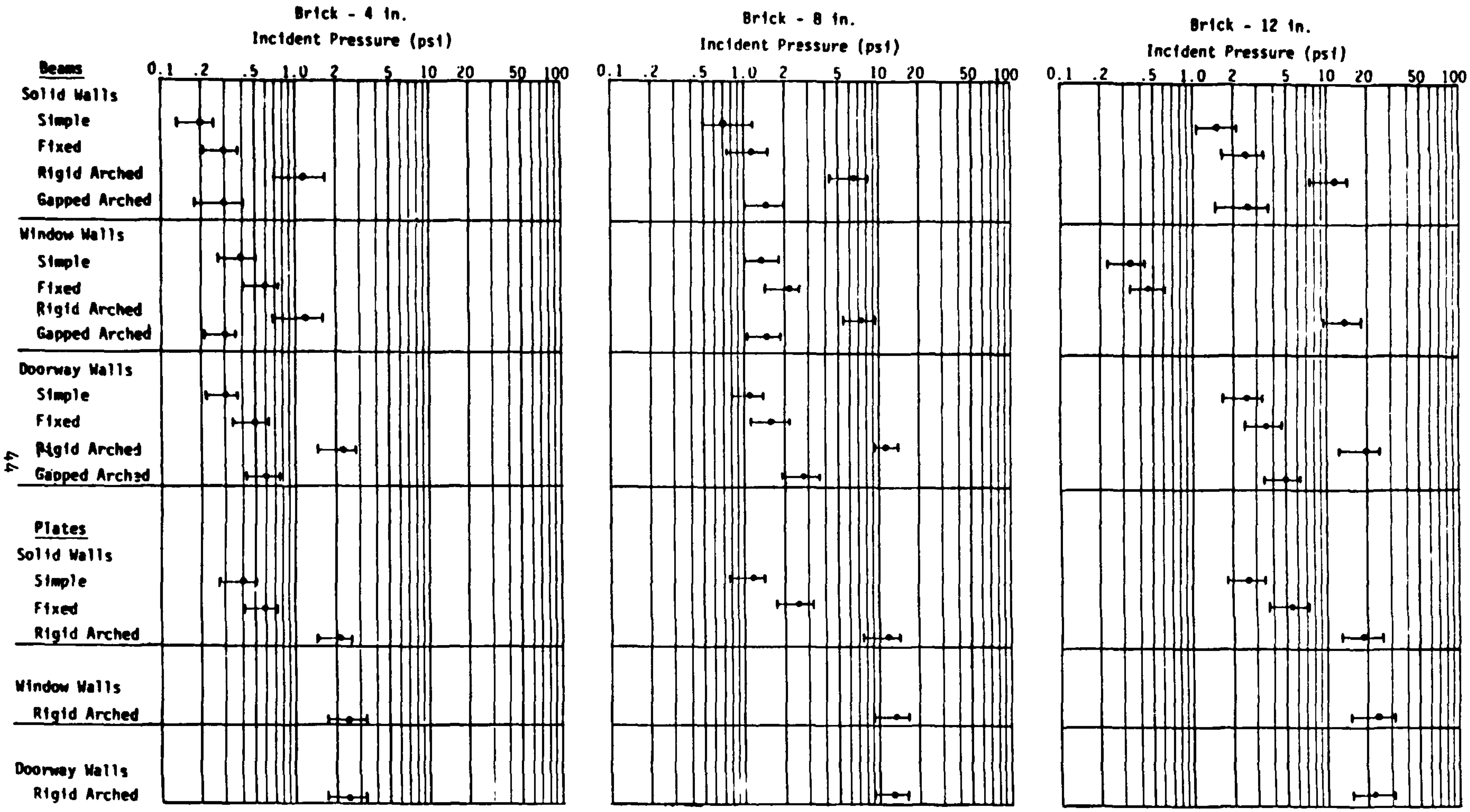
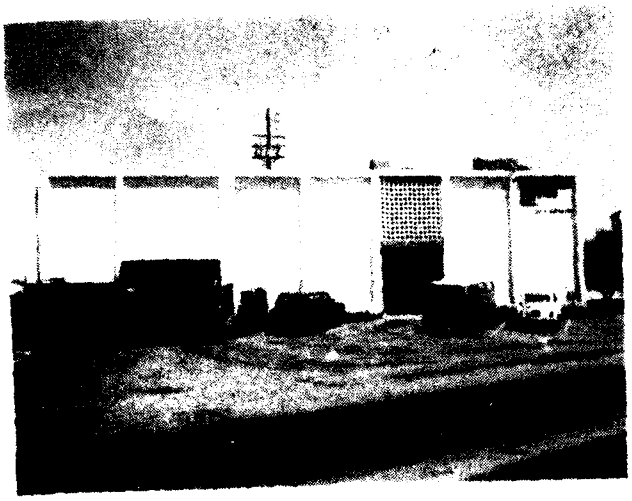
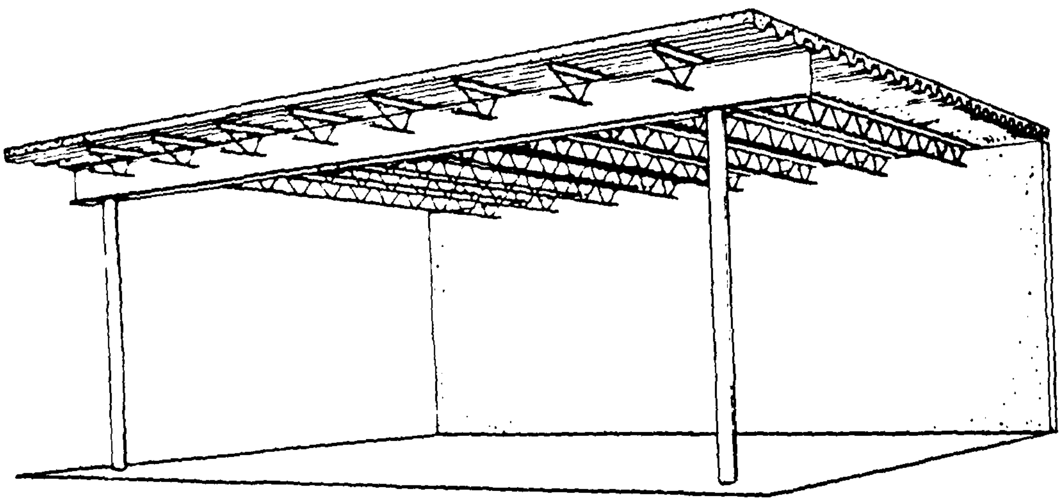


TABLE 14: FAILURE MATRIX FOR WALLS (contd)





A. Tilt-Up Construction



B. Steel Joist Roof Construction

Fig. 8. Typical Industrial Buildings.

A second common building is the steelmill type of building, which is a steel frame, usually clad with metal or corrugated asbestos sheathing, with, in general, many windows. In the pressure domain of 2 to 5 psi, there will certainly be some collapses, but in most cases, the sheathing will be stripped from the frames and there will be considerable frame distortion. Obviously this type of failure will generate huge quantities of debris, which will scatter out across the facility as well as adjacent facilities. These mill-type buildings are generally carefully engineered and the damage and collapse loads are fairly predictable.

A third category of industrial building, found mostly in the eastern portion of the United States, is the brick bearing-wall type of structure with the floors and roof structures being of either wood or steel. These buildings often have large window openings, so that glass failures would be expected at 0.5 psi or less, wall failures in the domain of 0.5 to 2 psi, and roof collapse, from 0.5 to 1 psi. The floors, in those that are more than one story, are generally designed as manufacturing floor load, and the floors themselves would be expected to withstand as much as 2 to 3 psi.

It will be noted in the above discussion and in the data in Tables 12 through 14 that, for industrial structures, it is expected that there will be minimal damage at perhaps the 0.2 psi level, to heavy damage in the range of 2 to 4 psi, and little chance of survival above 5 psi. This is also illustrated in Figure 9, which indicates light, medium, and heavy damage as a function of overpressure predictions for the ten classes of buildings previously presented in Table 7. Table 15 presents predictions for other types of industrial structures, utilities, and equipment.

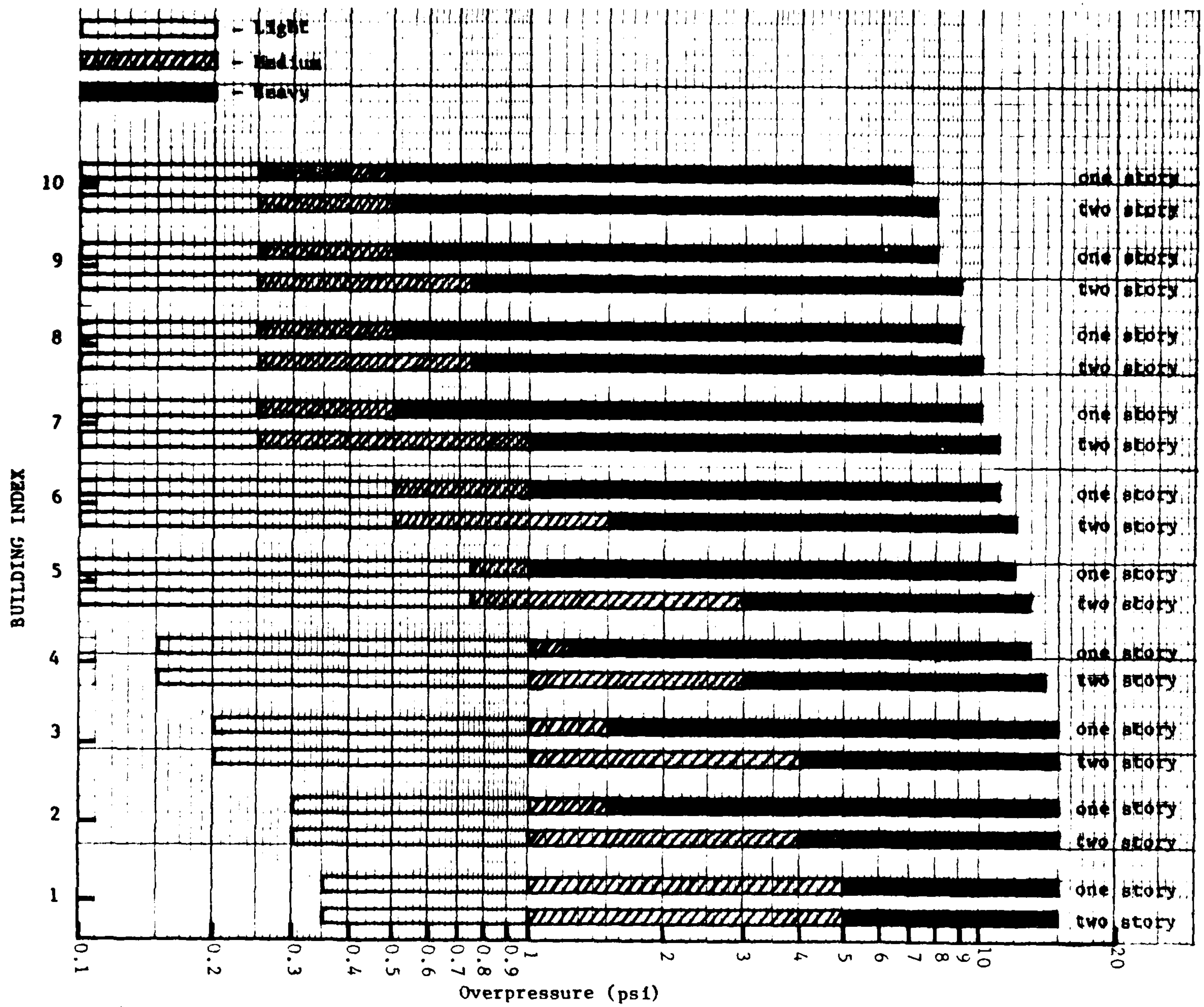


Fig. 9. Building Index vs Degree of Damage at Various Overpressures.

TABLE 15: DAMAGE PREDICTIONS FOR SELECTED EQUIPMENT

Type of Equipment	Overpressure (in psi) at which Damage is Predicted		
	Light	Medium	Heavy
Railroad Equipment			
Boxcars	2	4	6
Diesel locomotives	6		
Aircraft			
Transport aircraft	1	2	3
Light liaison aircraft	0.5	1	2
Helicopters	0.5	1.5	3
Vehicles			
Cars, trucks, buses	1	—	5
Utilities			
Wood poles	1	—	3.5
Steel electric towers	1	2.7	5
Industrial Equipment			
Heavy machine tools	—	10	—
Light machine tools	3	—	10
Oil storage tanks	—	—	3.4
Mobile Items	1	1.7	—

SECONDARY FIRE HAZARD INDICES

The purpose of the model is to provide a very simple, general technique to get a numerical estimate of the number of secondary fires expected to occur as a result of damage to an occupancy or defined building region, caused by a blast wave associated with nuclear detonations. The underlying basis of the model involves the use of Bayesian statistics.

Now, classical statistics are based upon the fundamental premise that the total of the quantitative knowledge of a particular parameter; e.g., a failure rate or, in this case, a frequency of fire occurrences per occupancy unit as a function of degree of damage of occupancy unit as a whole (building plus contents) is derived via inference from elaborate experimental data acquired from historical records or actual tests. In this instance, the key notion is one of "objective probability". That is, until experimental observations/information have been accumulated, nothing is known about the inherent probability of occurrence of events of interest (the number of expected secondary fires associated with multi-megaton bombs released in the vicinity of critical industries).

On the other hand, a Bayesian approach employs a notion of "subjective probability" - a theory that accepts indirect evidence from observations of events that may be only physically somewhat similar to the event of interest. As well, a good deal of engineering judgment involving best estimates of a sequence of events and their relevance to an expected sequence of events that has never occurred may also provide the indirect evidence. Given the day-to-day existence, or potential existence, of some form of ignition source (flame, electric arc, thermal energy release) and a combustible material supply (as built, contained, or released as a function of degree of physical damage to an occupancy), a logical assumption can be made about the extent of interaction of these items. For example, the extent of interaction can be assumed to behave in an exponential fashion when a hazard rate versus stress, or in this case frequency of fires per occupancy residency, is plotted as a function of degree of damage.

For other catastrophic events, ranging from equipment failure to chain reactions, nature in general responds in a non-linear fashion. However, with regard to the estimation of secondary fire occurrences for a particular damaged occupancy unit, it is necessary to establish a bound to the upper limit of the number of distinct fires that can be initiated before the individual fires lose their definition and become a single continuum fire totally involving all the available combustible materials in a single fire. From a secondary fire origination viewpoint, it is very important to be able to estimate the increased number of occurrences or sources of secondary fires (with damage) since it follows that the greater the number of initial sources, the more rapid the fire involvement; the more difficult the task of successful fire control/extinguishment, the more rapid the destruction or extent of damage to a particular occupancy.

In its most simple form the Bayesian approach accepts, in principle, a subjective estimate through reasoning that has been made in as logical, consistent, and methodical way as possible. The estimate, in turn, can substitute effectively for non-existent "hard" data, in the final decisionmaking process. The method is particularly powerful for application to large scale systems because large uncertainties in the estimate produce small changes in the prediction (as will be seen later). The most common use of the Bayesian statistics occurs in treatment of different, available or proposed, estimates of the same hazard parameter, which in this case is the estimated number of secondary fires for a particular undamaged/damaged occupancy unit. In application, a notion is assumed that any or all of the estimates of the hazard parameter are valid and, collectively, they include a lot of subjective data condensation and sampling variations. It is further assumed the true value of the hazard parameter will be drawn at random from a distribution encompasssing "any available" or "proposed" estimates. The mean of the distribution is then the expected number of secondary fires per defined occupancy unit, and its variance simply defines the uncertainity in the actual outcome. A log normal distribution is fitted to the estimate as an approximation, basically because experience indicates that the "a priori" distribution, more often than not, takes this form. General discussion, more often than not, generates further practical and theoretical arguments in support of such an assumed distribution. It must be noted the hazard parameter does not change markedly with time and the estimated number

of secondary fires per defined occupancy unit does not change with time. Any log normal distribution consideration then must describe only uncertainty in the hazard parameter value, not its functional variation with time.

The alignment chart used to estimate the number of secondary fire occurrences is an extension of NFPA data for 1979, where the estimated number of fires in all structures in the United States that were reported (Ref. 18, page 54) was 1,036,500. Historically, the number of reported fires are only a fraction (approximately 8%) of the number of fires estimated to have actually occurred, but were never reported to NFPA. In 1979 a **total** of 2,845,000 fires of **all types** were reported. This means about 35 million fires were not reported. If these latter unreported occurrences all were visibly significant, there would be about 16,000 fires per 100,000 people, or about 0.16 fires per person, annually. Such a "burning of America" can not be observed in actuality, and the reported fires (about 1,280 per 100,000 people or 0.013 fires/person annually) are more representative of the standard annual fire event picture in the United States. Typical **unreported** events could involve the ignition of scrap paper in a waste basket, some furniture, or a stovetop fire; ignition of an oil rag or solvent; a laboratory-desk fire; an electrical short circuit that locally ignites some combustible debris; a local process overheat, or thermal release, that triggers one or two sprinkler heads or smoke/flame detectors; an overheated electric motor. All such incidents would quickly and quietly be remedied without reporting (for insurance purposes or otherwise). At the same time it is suspected many of these incidents would probably burn out by themselves when the limited fuel supply was consumed.

Using the standard estimates of fire occurrences in **all structures** — the number of reported annual fires (1,036,500), an estimate by the U.S. Bureau of the Census of 250,000 residential occupancy units per million population (which represents over 90% of the "structural" units in the United States), and the 1979 population estimates (221,000,000 people) — results in a fire frequency per occupancy unit of about 0.019.

Now with an **average** building index of about 7, a contents index on the order of 5, the alignment chart as constructed yields the estimated number of fires

(approximately 0.019) that are now reported to occur on an annual basis to **all** structures under standard conditions. The individual building and contents scales, ranging in value from 1 to 10, can be reevaluated to represent exceptional conditions; e.g., changing a contents index to reflect the obvious increase in potential fire hazard when quantities of very flammable liquids are simply stored in a structure. In such cases, the contents index would be increased in value to 8 or 9, which, for an average building index, would result in about a tenfold increase in the estimated number of fires possible for this particularly high risk industrial or residential scenario.

Conversely, there is a limited range of reduction of the contents index for a given building to reduce the standard number of fires per occupancy unit. In this way reducing the combustible rubble/refuse in and around the residential unit obviously reduces the potential for fire damage. Equally obvious is the need for judicious application of all indices to yield a "standard" number of fires.

With regard to the damage scales, which yield an estimate of the expected secondary fires per **damaged** unit, for the "standard" residential unit with three levels of damage described in the text, the number of secondary fires per occupancy unit goes up exponentially — e.g., for general residential occupancy the standard, light, medium, and heavy damage conditions yield 0.019, 0.028, 0.05, and 0.64 fires expected per occupancy unit. The slight damage category might include broken windows with the air jet having knocked over appliances, broken lights, and shorted wires, sloshed a pan of grease on a hot element or swept combustible debris to an ignition source. The badly damaged to collapse estimate would result in enormous accumulations of combustible debris, missile-perforated containers, broken wires, sheared gas/oil pipelines, and stacked debris.

The assembled building index, contents index, the standard, and the light, medium, and heavy damage scales are shown on Figure 10. On the far right side of the alignment chart is what is called the standard index. This presents the data for normal fire experience as a function of the building and contents indices. To test the validity of this index, six data points were used: the National Fire Data Center data on residential fires, as presented in Ref. 19, and selected data on fires in

1. Financial/Banking
2. NFDC Data
3. Service Stations
4. Auto Shops
5. Paint Warehouses
6. Bulk Fuel Storage

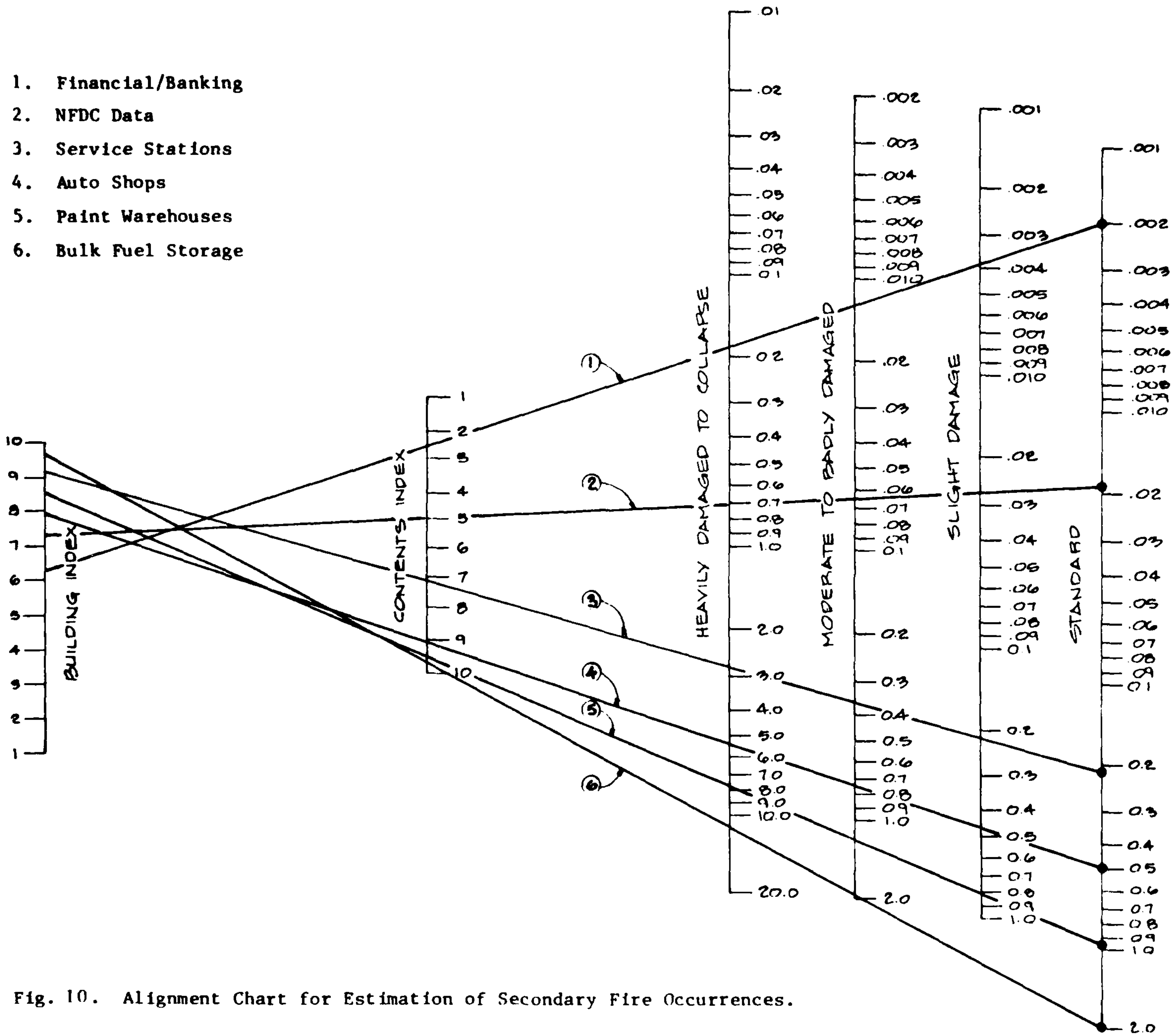


Fig. 10. Alignment Chart for Estimation of Secondary Fire Occurrences.

various occupancy classes -- financial/banking, service stations, auto shops, paint warehouses, and bulk fuel storage — from Ref. 3. The other three indices indicate the expected number of secondary fires per structure or occupancy unit as a function of light damage, moderate to bad damage, and heavy damage to collapse. The validity of these indices was tested by using available data. Examples of the types of data used are provided for Hiroshima/Nagasaki in Figure 11, and for earthquakes in Figure 12.

It is interesting to compare the results of the model with the Ref. 3 conclusions, which were 0.006 ignitions per 1,000 sq ft of total floor area damaged at 2 psi. Using the average square footage of the Nagasaki and Hiroshima structures, this would convert to approximately 0.07 secondary ignitions per structure on the moderate to badly damaged scale. Using the average contents index of 5 and a building index of approximately 7.5, which is not too different from many of the Japanese structures analyzed, the model also predicts 0.07 secondary ignitions per structure; the model also predicts 0.7 fires in the heavily damaged region and 0.03 secondary fires for the light damage region.

1 - Wood Machine Shops-Nagasaki (Ref. 5)
2 - Combined Manufacturing-Hiroshima/Nagasaki (Ref. 3)
3 - Combined Mercantile Category-Hiroshima/Nagasaki (Ref. 3)
4 - Reinforced Concrete Machine Shops-Nagasaki (Ref. 5)
5 - Steel Frame Machine Shops-Nagasaki (Ref. 5)

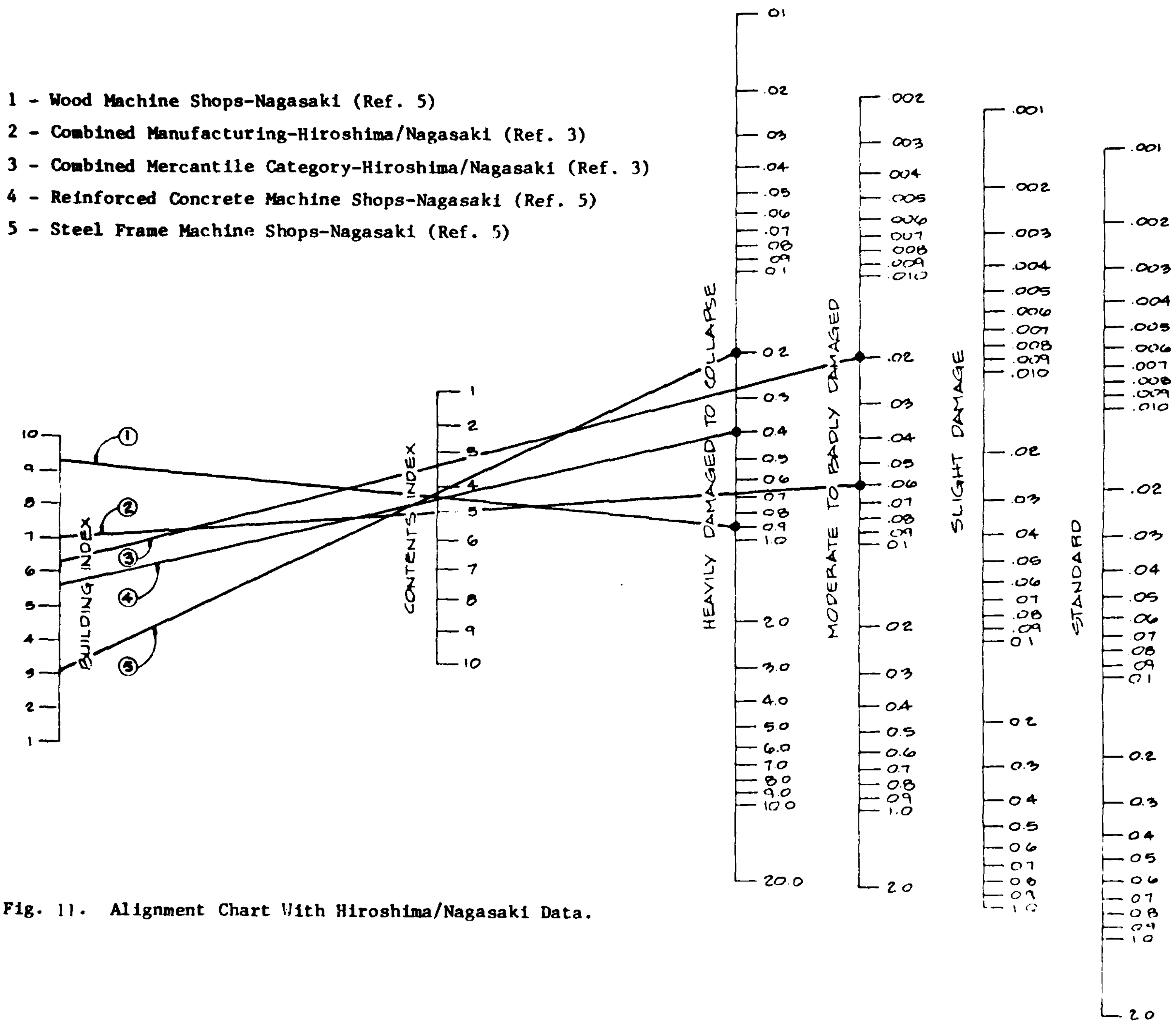


Fig. 11. Alignment Chart With Hiroshima/Nagasaki Data.

1. Bakersfield and San Francisco
2. Selected Structures, San Fernando
3. Anchorage

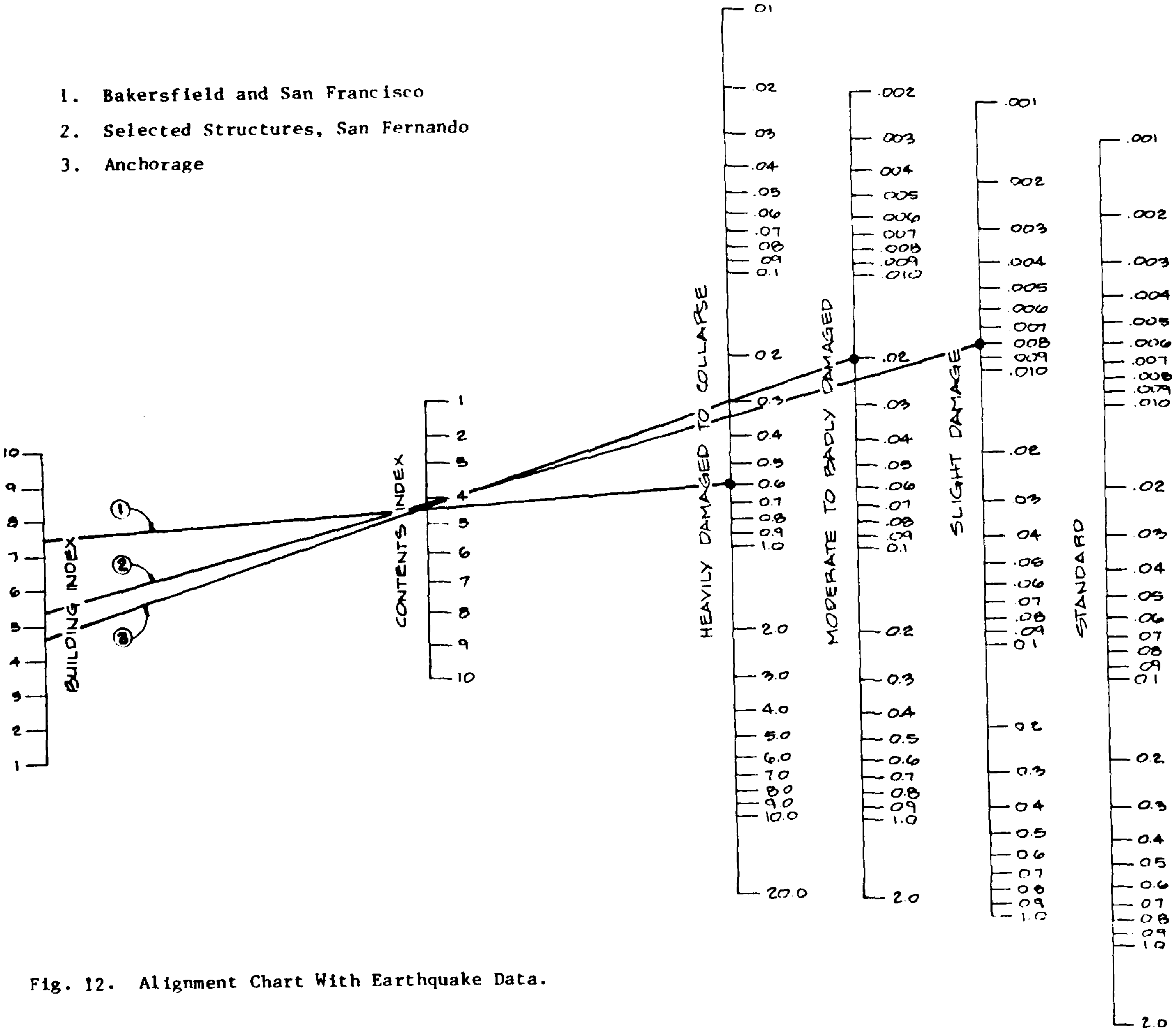


Fig. 12. Alignment Chart With Earthquake Data.

Section 4
THE MODEL

In the previous section the development of the secondary fire prediction model was described. In this section, which can be easily adapted into a field use package, the use of the model is explained.

All necessary data are supplied, with the exception of the psi level to be expected at the facility. It is not known at this time whether definitive predicted psi information will be available from local civil defense authorities in all areas. If none is available it will be necessary to assume the worst, such as heavy damage, for the prediction procedure. If a crisis relocation plan has been developed, however, it will usually include an evacuation zone. The outer boundary of this zone is usually established at the 2 psi ground range (or in some rare cases 3 psi) from a predicted attack. Using this boundary line and distances from the line, either toward or away from the attack point, it is possible to extrapolate a predicted psi value for a particular location and weapon size. (A representative range of sizes is 1 to 20 MT.) To aid in extrapolating from this line refer to Figure 13, which gives the ground ranges for various sizes of megaton weapons for overpressures from 15 to 0.1 psi.

The steps in using the model are shown on the worksheet, Figure 14. They are as follows:

1. List facility name and address or identification number.

2. Identify type of occupancy (machine shop, etc.)

3. Select construction type from building index in Table 16 and Figure 15 (e.g., sheet metal storage shed = 10; concrete block warehouse = 8, etc).

4. From Step 2, type of occupancy, select contents index number from Table 17 (custom machine shop = 4.1; service station = 8.2, etc.). Note, for multi-use facilities, either divide facility and make estimates for each occupancy area, or use most hazardous occupancy (i.e., higher contents index number). Also, if hazardous/flammable/combustible materials are in a protected location (e.g., behind firebreak or underground) make contents index one point lower; i.e., service station becomes 7.2 instead of 8.2.

5. List expected overpressure at the facility, either obtained from civil defense sources or extrapolated from Figure 13.

6. Select appropriate damage level (light, medium, or heavy) from index using expected overpressure and overpressure damage estimate from Figure 15.

7. Using a straight edge, line up selected building index with contents index, and extend to intersect the appropriate damage index on alignment chart, Figure 16. Read predicted secondary fire estimate on right side of damage index and record on worksheet (Figure 14).

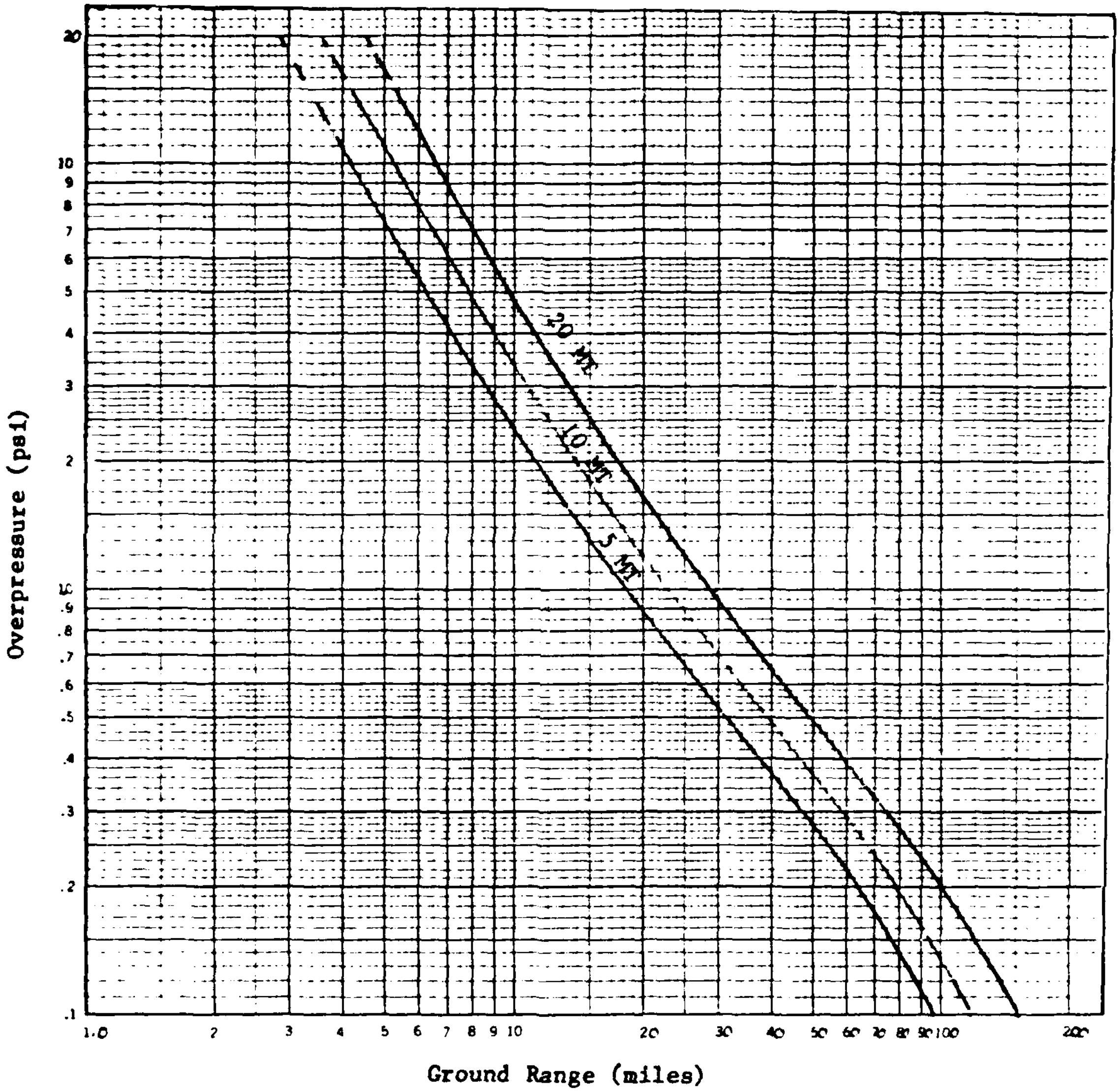


Fig. 13. Pressure-Distance Falloff Curves for Bursts Intermediate Between Surface and Optimum Height.

1	2	3	4	5	6	7
FACILITY NAME OR NUMBER	FACILITY TYPE	BUILDING INDEX	CONTENTS INDEX	EXPECTED OVER PRESSURE (PSI)	DAMAGE LEVEL	NUMBER OF FIRES PER UNIT

Fig. 14. Worksheet.

TABLE 16: BUILDING INDEX

1. **Heavy Design**
   Reinforced concrete structures designed for protective purposes (e.g., bank vaults, nuclear containment vessels and control rooms)

2. **Heavy Design**
   Reinforced concrete walls, roofs, and floors or heavy steel frame, metal deck supported by steel purling, with reinforced concrete topping; walls of concrete block or brick (e.g., heavy manufacturing, power plants, storage warehouses)

3. **Heavy Design**
   Reinforced concrete frame with precast concrete walls, floors, and roof; or heavy timber frame with heavy timber floor and walls of concrete block or brick (r.g., heavy manufacturing, office buildings, warehouses)

4. **Medium Design**
   Precast concrete frame with precast walls, floors, and roof, or heavy timber frame with medium loading floors and walls of concrete block or brick, or medium design reinforced concrete walls, floors, and roof (e.g., light manufacturing, large retail or wholesale stores)

5. **Medium Design Load**
   Concrete block or brick wall, precast concrete floors/roof, with wall openings of more than 10% (light manufacturing, retail and wholesale stores, light storage warehouses)

6. **Medium Design Load**
   Concrete block or brick walls, precast concrete roofs/floors with less than 15% wall openings; precast concrete walls with precast concrete floors and roofs (pumphouses, mechanical equipment buildings, storage buildings, water and sewage treatment plants, light manufacturing)

7. **Light Design Load**
   Concrete block or brick walls, timber roofs and floors with more than 15% openings in walls (retail stores, motels, professional buildings, office buildings)

8. **Light Design Load**
   Concrete block or brick walls, timber roofs and floors with less than 15% wall opening (mini warehouses, construction storage buildings)

9. **Light Design**
   Precast concrete walls with timber joist roofs and floors or steel joist roof and floors; light steel frame, infill walls with steel joists and roofs (warehouses, office buildings, and light manufacturing)

10. **Light Design**
    Wood/metal stud walls, with siding, stucco, brick veneer; timber joist or glulam roofs and floors; light corrugated metal walls and roofs (residences, restaurants, small retail stores, storage sheds, light manufacturing)

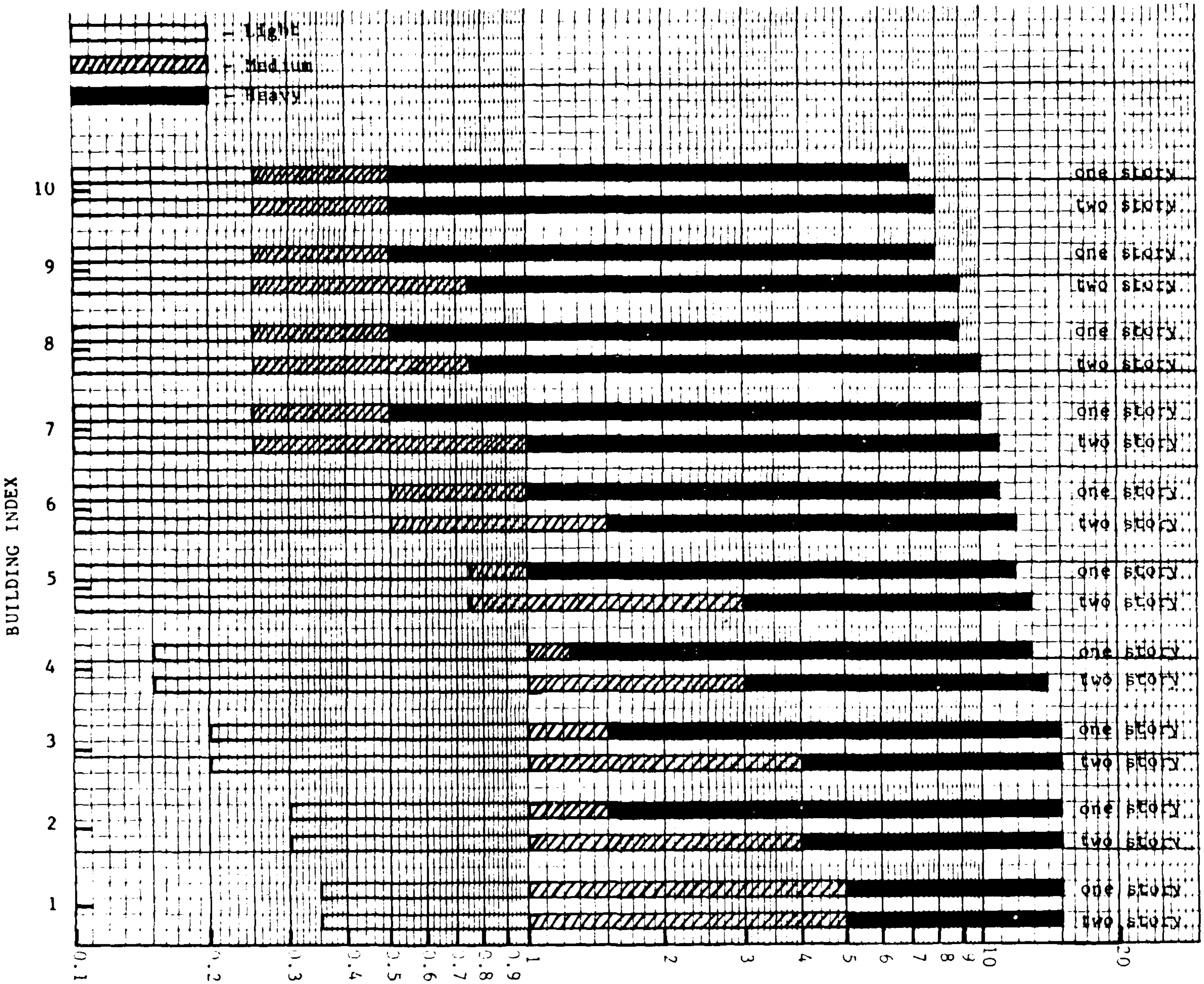


Fig. 15. Building Index vs Degree of Damage at Various Overpressures.

TABLE 17: CONTENTS INDEX

Agriculture/Food
Bakeries, bread producing - 2.6
Bakeries, with donut production - 5.6
Candy manufacturing - 5.7
Canneries - 2.2
Creameries, ice cream manufacture - 2.1
Dairy farms - 6.5
Farming, field crops, poultry, and eggs - 4.3
Lard, tallow, etc., rendering plants - 8.7
Meat packing, including slaughtering - 4.5
Meat products, preparation and packaging - 6.3
Poultry products processing - 6.6
Produce, food processing - 3.4
Ranching, cattle and other livestock - 5.8
Vegetable oil processing - 6.4

Chemicals and Plastics Manufacturing
Fiberglass boat manufacturing - 9.1
Hazardous (combustible or flammable) chemicals -9.6
Paint manufacturing, including storage - 9.2
Plastic products, including foams, manufacture - 9.3

Communications Facilities
Fire, police communication facilities - 5.0
Radio and television stations - 5.0
Radio and television transmitters - 8.0

Electrical Equipment Manufacturing
Electrical hardware manufacturing - 3.7
Electrical equipment manufacturing - 1.8
Heavy electrical equipment manufacturing 1.6

Electronic Equipment Manufacturing
Communications equipment (telephone) - 4.0
Electronics equipment manufacturing - 4.6
Electronic semiconductor manufacturing - 8.1

Fuels
Coal gasification plants - 9.4
Petroleum refineries - 9.7
Service stations - 8.2

Foundries and Machine Shops
Custom machine shops - 4.1
High speed machining and screw machines - 6.7
Metal fabrication, welding shops - 4.2
Nonferrous metals, refining and foundries - 1.4
Punch press and steel stamping plants - 1.9
Steel smelting, foundries and forge shops - 1.5

Glass/Ceramic Manufacturing
Glass container manufacturing - 3.5
Glass, flat plate manufacturing - 2.8

Medical Facilities
Convalescent homes - 3.0
Hospitals - 3.1

Mining and Quarries
Coal mine facilities - 7.0
Quarry and ground pit operations - 1.1

Offices, Schools, etc.
Churches and church schools - 3.9
Colleges and universities - 3.2

Offices, Schools, etc. (contd)
High rise hotels, apartments, and offices - 7.5
Hotels, motels (not high rise) - 5.2
Libraries - 3.6
Offices, including banks - 2.7
Primary and secondary schools - 3.3

Paper Manufacturing
Coated paper and plastic laminate manufacturing - 8.8
Paper, box and carton manufacturing - 6.0
Paper manufacturing, heavy - 2.3

Printing Facilities
Printing, job shops - 6.9
Production printing plants -5.5

Storage Facilities
General storage warehouses - 7.1
Marine storage facilities, yards and shops - 7.7
Record storage - 6.1
Warehouses and distribution centers - 5.3

Textile Manufacturing
Textile and garment manufacturing - 5.4
Textile mills using cotton and synthetics - 6.8

Transportation Facilities
Aircraft hangars - 5.9
Busline facilities, including shops - 7.9
Rapid transit facilities - 4.8
Railroad freight terminals - 7.2
Railroad shops and yards - 2.5
Ship terminal facilities - 4.7
Shipyards - 4.9
Truck freight terminals - 7.4
Truckline facilities, including shops - 7.3

Utilities
Electric power generation plants - 1.7
Electric power substations - 3.8
Sewage system facilities, pumping plants - 1.3
Water system facilities - 1.2

Vehicle manufacturing and service
Aircraft maintenance shops - 7.8
Aircraft manufacturing - 7.6
Auto body shops - 9.0
Automotive repair shops - 8.2
Engine, pump, and turbine manufacturing - 2.9
Mobile home manufacturing - 8.4
Truck, bus and railroad equipment manufacturing - 2.4

Wood Products Manufacture
Woodworking and furniture factories - 8.5
Sawmills - 8.6

Miscellaneous
Asphalt plants - 8.9
Autoignition materials handling facilities - 10
Computer installations - 5.1
Explosives and pyrotechnics manufacturing - 9.9
Gypsum wallboard manufacturing - 2.0
Ordnance manufacturing - 9.8
Retail stores - 6.2

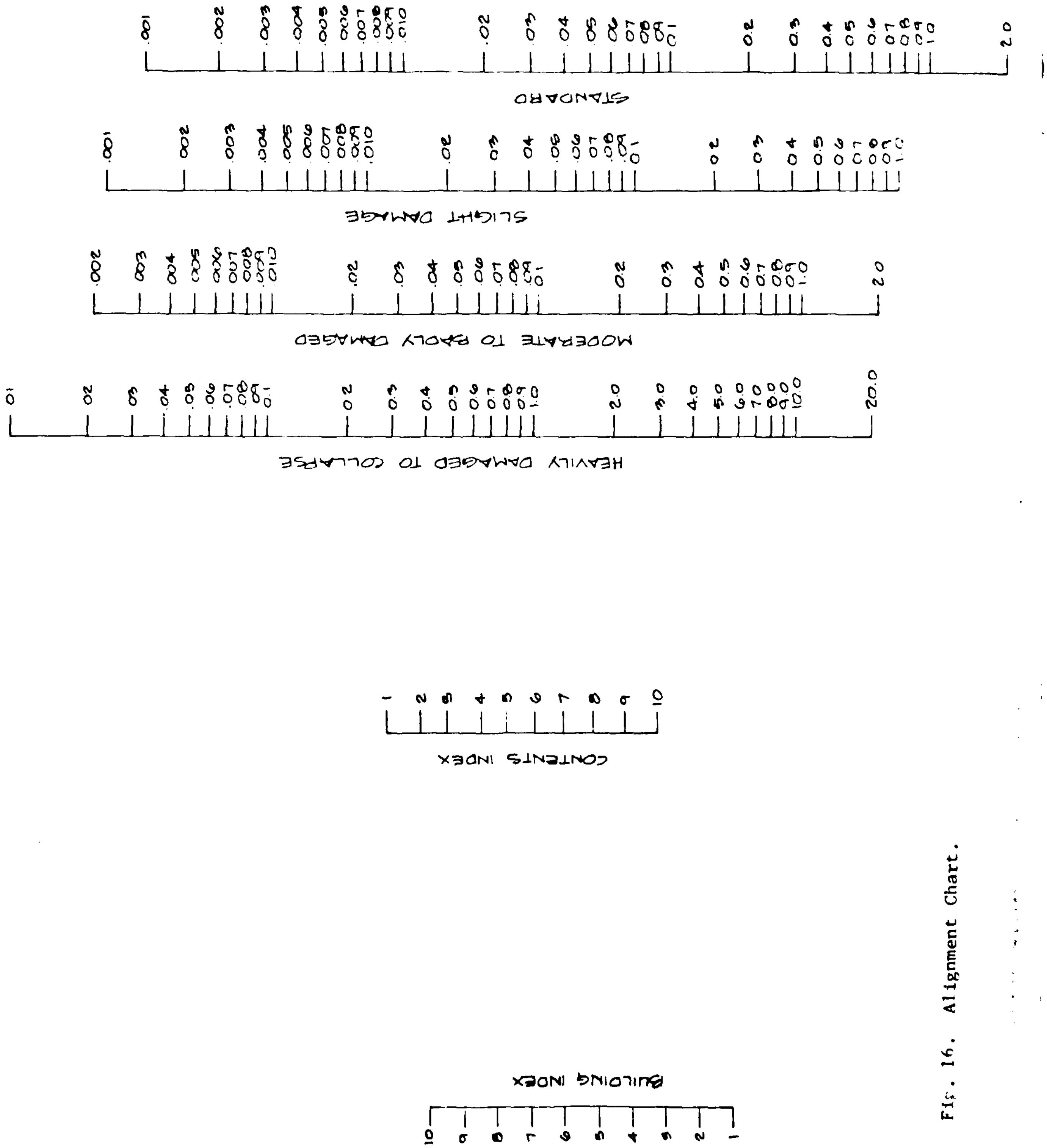


Fig. 16. Alignment Chart.

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APPENDIX A

Earthquakes

Appendix A
EARTHQUAKES

COMPARISON OF EARTHQUAKE LOADING AND BLAST LOADING

Can earthquake loading and blast loading be related? Unfortunately, any simple comparison is deceptive, at best. This appendix describes the underlying differences in the application of energy induced forces as these forces affect structures.

Initially, it seems possible to compare the two phenomena, i.e., to describe earthquake energy release in equivalent tons of TNT used to describe nuclear blast effects (see Figure A-1). Richter scale magnitude, or similar magnitude measurements assigned on the basis of seismograms do not directly measure energy. An empirical formula is used to relate earthquake magnitude to energy.

Richter scale. Magnitude = $1/1.8 \log E/E_o$

E is energy of event to be measured,

E_o = standard equivalent of "zero" magnitude accepted to be 2×10^{11} ergs

The energy of 20 KT burst = 8×10^{20} ergs

R magnitude of 20 KT = $1/1.8 \log 8 \times 10^{20}/2 \times 10^{11} = 5.3$

Energy is not even a sufficient index for comparison of the severity of two earthquakes. Thus, comparing energy as a measure of the severity of an earthquake to blasts is more difficult. The 1971 San Fernando earthquake had a magnitude of 6.6, the magnitude of the 1906 San Francisco earthquake was 8.3. In terms of energy, the 1906 event would appear to be more than 350 times greater. A similar comparison with the 1933 Long Beach earthquake (M = 6.3) indicates the 1906 quake had 1,000 times more energy.

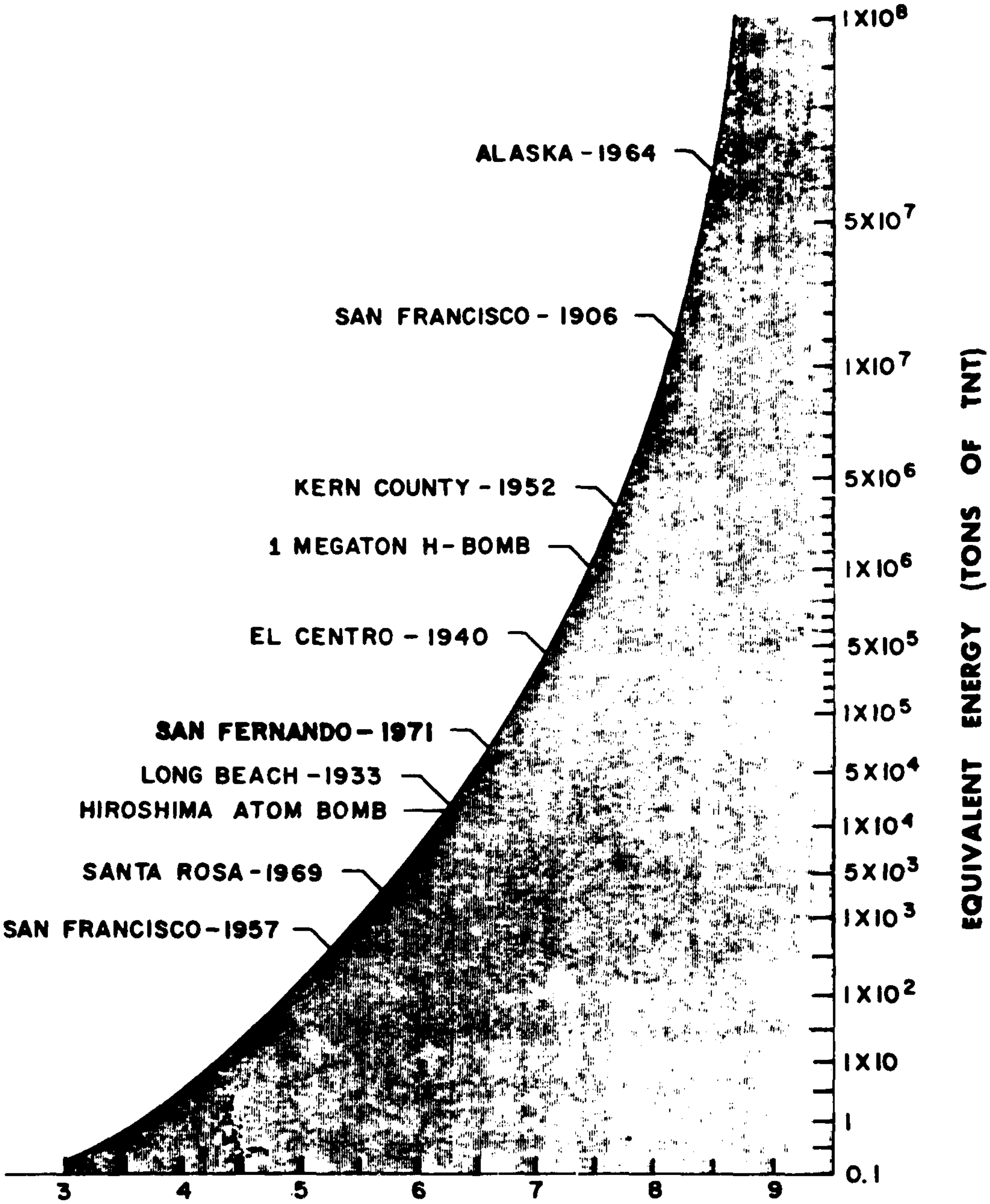

Fig. A-1. Richter Scale of Magnitude. Comparison of Richter Scale of Magnitude versus Equivalent Energy of TNT.

Source: "Engineering Aspects of the 1971 San Fernando Earthquake", National Bureau of Standards, 1971, p 11.

Is the energy release relationship between two earthquakes significant, in terms of ground shaking or destruction or loss of life? Apparently not. For example, the 1971 San Fernando earthquake was probably the equal of 1906 in terms of intensity. The energy release of the 1971 event resulted in a duration of strong shaking of approximately ten seconds, compared with the 45 seconds in 1906. Yet, in the 10 second period, the shaking was sufficient to load some structures to failure. It is unlikely that the peak ground acceleration of 1 g recorded in 1971 was exceeded in 1906, though no 1906 acceleration data are available. The intensity of ground motion of the 1933 Long Beach earthquake was probably less than that in 1906, but not 1,000 times less intense, using existing state-of-the-art engineering.

In terms of dollars and loss of life, was the 1906 earthquake a thousand times more destructive than the 1933 Long Beach earthquake? Approximately 100 people died in the 1933 event and 700 to 800 died in 1906. In current dollars, the economic loss for the destruction in 1933 was 266 million. If 1906 were a thousand times more destructive, the loss would be 266 billion, yet the actual loss was 333 million in current dollars (Ref. A-1).

Earthquake engineering experts recognize that, as the magnitude of an earthquake exceeds a threshold value of Richter 5 or 6, the loading and damage resulting therefrom varies over a wide range. The severity depends on numerous other factors not included wholly within the Richter magnitude concept of total energy release.

Since energy does not adequately describe the practical or engineering effects of earthquakes, energy per se is an inadequate measuring stick for comparison of earthquakes and blast. Consider Figure A-1: the 1933 Long Beach earthquake and the Hiroshima nuclear bomb were approximately equivalent in energy, but there is no further significance to this equivalence. The blast loading imposed on buildings within a few thousand feet of ground zero at Hiroshima was sufficient to cause complete destruction. In Long Beach, numerous unreinforced masonry buildings and other relatively unengineered structures remained standing, even in the "bulls eye" or isoseismal zone of greatest shaking. Valid comparisons cannot be developed for

any of the other earthquake/nuclear event pairings on the Figure A-1 curve, such as the 1906 earthquake and an equivalent 20 MT nuclear weapon.

COMPARISON OF EARTHQUAKE AND BLAST DAMAGE

To summarize the comparison of earthquake and blast damage in broad terms, severe earthquake damage resembles light to moderate blast damage. The worst damage an earthquake can cause is structural collapse. Nuclear blast damage however, in the 2 to 5 psi range, may be sufficient to completely disintegrate large buildings and scatter debris over large areas. With a given population of earthquake resistant buildings constructed under recent seismic codes, an earthquake of destructive Richter magnitude will cause only a small number of the structures in the area of heaviest shaking to collapse. In the absence of modern earthquake design code provisions, as existed in 1906, no buildings over 8 stories in height collapsed. Under blast loading, in the 2 to 5 psi range, many of these same buildings would have sustained severe damage or collapsed.

Most structures subjected to earthquakes have sustained damage ranging from superficial to moderate (i.e., no major structural failure - generally repairable damage). The only earthquakes where entire towns or large urbanized areas have in general been destroyed have been those similar to the 1960 Agadir, Morocco event. The buildings were not constructed using earthquake-resistant building codes similar to those in California. By comparison, detonation of a nuclear weapon in the one kiloton range in an urban area would cause complete destruction over a sizable area. Complete destruction of nearly all buildings, including structural steel and reinforced concrete types of construction, extends to about 4 miles, or an area of 12.6 square miles for a 20 MT size weapon. Buildings can be designed and constructed to resist the worst possible earthquake forces with only moderate damage. To design and construct these same structures to resist blast is several orders of magnitude more difficult.

It should be noted that many light wood-frame structures and metal-framed industrial buildings are highly resistant to earthquake damage, but are destroyed at low blast overpressure levels.

COMPARISON OF SEISMIC AND BLAST SECONDARY FIRES

Earthquakes and blasts damage structures via different mechanisms, and these qualitative differences must be considered when comparing the two phenomena for predicting the incidence rate of blast-caused fires and for estimating the distribution according to specific types of ignitions. It has been observed that earthquake-resistant buildings (such as some of the Japanese structures in Hiroshima and Nagasaki) are generally more blast resistant than similar non-seismically designed counterparts. However, earthquakes and blast result in dissimilar structural loads and damage. Table A-1 appears to indicate a close correspondence of earthquake and blast damage levels. A detailed consideration of the facts presented in this table leads to the opposite conclusion.

Light Damage

At the light damage level, equipment can move enough to rupture gas piping or electric wiring, and these two hazards will account for most earthquake-caused fires in a contemporary U.S. city. In the case of blast, the windows and doors, papers, and other light objects will become airborne missiles and be turned into debris. The water heater or furnace typically located in an enclosure will probably be undamaged. At this lower level of damage, the main result of blast damage is debris. Non-structural drag sensitive as well as "statically" loaded components are damaged and lightweight objects (paper, books, glass, metal cladding, pieces of wood) are scattered.

This debris becomes fuel to pre-existing ignition sources (open flames, industrial processes, as examples) and new ignition sources (sparks or hot metal caused by impact, friction, tearing, or ignition by reactions of spilled chemicals, as examples). Downed electrical wires, when still charged, would be a significant and potentially widespread ignition source. Paper products would be the most significant source and become debris fuel readily after windows shatter at about 0.33 psi.

At the light level of earthquake damage, debris-caused fires may also occur. Examples would include such 1971 San Fernando earthquake incidents as the falling of candles, wood, or plastics onto ignition sources in dwellings. Earthquake fire

TABLE A-1

COMPARISON OF EARTHQUAKE AND EXPLOSION DAMAGE LEVELS

DAMAGE LEVEL	EARTHQUAKE	NUCLEAR EXPLOSION
LIGHT	WINDOWS OR PARTITIONS CRACKED; BRITTLE, HEAVY APPENDAGES LOOSENED OR FELLED; EQUIPMENT SHIFTED; CHIMNEYS DAMAGED	WINDOWS & DOORS BLOWN IN; PARTITIONS CRACKED, BUT INTACT; LIGHT OBJECTS TRANSPORTED AS DEBRIS; CHIMNEYS DAMAGED
MODERATE	STRUCTURAL FRAME AND/OR WALLS PERMANENTLY DISTORTED, BUT INTACT; PORTIONS OF CEILING COLLAPSED; EQUIPMENT OVERTURNED	STRUCTURAL FRAME AND/OR WALLS PERMANENTLY DISTORTED, BUT INTACT; PARTITIONS AND PORTIONS OF ROOF COLLAPSED; EXTENSIVE NONSTRUCTURAL DEBRIS INCLUDING HEAVY OBJECTS SUCH AS PIECES OF MASONRY OR METAL
SEVERE	PARTIAL OR TOTAL COLLAPSE, OR SHATTERED BEARING WALLS OR SEVERELY DISTORTED FRAME	PARTIAL OR TOTAL COLLAPSE OF STRUCTURE, OR SHATTERED BEARING WALLS OR SEVERELY DISTORTED FRAME. DEBRIS INCLUDES LARGE HEAVY OBJECTS

ignition, however, is a rather minor damage category. Debris seems to be much more significant for blast-caused fires than for the earthquake-caused fires.

The downed-wire problem is quite significant for earthquakes at a relatively low level of general damage, light shaking caused only slight damage to typical structures. At distant locations where only a few buildings in the entire area were significantly damaged, electrical lines came down in the 1971 San Fernando earthquake. Earthquake-caused electrical line failures may be comparable to blast-caused damage to overhead wires, which can occur at distant locations.

Another major category that can cause fires with light damage levels is lateral movement of heaters, furnaces, and appliances; this is much more of an earthquake than a blast problem. In general (for the range of relatively short frequencies typical of free-standing objects and equipment), the greater the mass, the greater the earthquake-induced force. In design terms, the earthquake-caused effective acceleration, multiplied by a larger mass, results in a proportionally larger lateral force. Large, massive objects may be easily moved by earthquakes, whereas the same mass is more difficult to shift or overturn by blast. Water heaters, furnaces, ranges, fan motors and compressors, and other equipment can be shaken enough by moderate earthquakes to cause gas pipes or electrical wiring to rupture, while their enclosing structures remain undamaged. This aspect is discussed further below.

Moderate Damage

At the moderate damage level (an overpressure of 2 to 5 psi, depending on type of structure) in the blast category, internal partitions and lightweight cladding may be destroyed. "Destroyed" in this case indicates that these components may become flying debris, rather than merely fail and collapse. There is substantially more debris consisting of paper, glass, books, and small objects. Large equipment is not translated or overturned at moderate damage levels.

In the case of earthquake-caused moderate damage levels, partitions may be badly damaged; i.e., drywall and plaster is cracked but intact, unreinforced masonry may crack, perhaps spall, and occasionally individual masonry units will drop. Gas piping or electrical wiring contained within these walls is more likely to be ruptured

by earthquake than by blast loading. Parapets and chimneys of an unreinforced masonry building are more likely to completely collapse in earthquakes than the building's bearing walls. False or drop ceilings and the associated electrical, air conditioning, and plumbing may partially collapse in earthquakes at this moderate damage level. Equipment suffers significant damage and translates laterally, causing structural deformation of gas piping and electrical wiring, resulting in rupture of the hookup.

At this moderate damage level, debris remains a prominent cause of blast secondary fires, but it is probably less significant for earthquakes. Gas and electrical equipment at this level are damaged if debris has impacted upon the equipment.

Severe Damage

At the severe damage level, any building damaged by nuclear blast has, by definition, collapsed. "Collapse", however, signifies a more devastating state than usually occurs with earthquakes. In addition to bringing the floors and roof to the ground, the blast forces will splinter wood members, rupture masonry, and thoroughly mix and scatter the debris. For earthquakes, most buildings in this severe level of damage are not totally collapsed. Portions of the roof may collapse, with walls standing, or vice versa. If the building "pancakes", the debris generally stacks vertically without significant lateral translation. Unreinforced masonry walls will be reduced to fragments, some as large, intact pieces. In general, the volume of debris would be sufficient in both the earthquake and blast scenarios to initiate a fire if an ignition source is present. Some blast debris has probably impinged upon nearby buildings.

It is apparent from this brief review of comparative seismic/blast damage levels that the level of equipment and building contents is significant. A few examples will illustrate the differences.

A 20-ton fire engine "jumped" 6 ft during the 1971 San Fernando earthquake. The wood-frame fire station housing the vehicle was severely damaged in economic terms (in part because of translation of the fire engine through the garage door), but

was left structurally intact (Ref. A-2). The movement of a massive piece of equipment and minor movement of the light wood- frame enclosure is not characteristic of blast damage. One would expect the light wood-frame garage to be severely damaged at 1 to 2 psi and to be reduced to splinters at 5 psi. In the 1955 Nevada nuclear tests (Ref. A-3), similar vehicles had dents and broken glass at 1 psi and at 5 psi most vehicles, though translated or overturned, remained operable.

It was observed by the Nagasaki Strategic Bombing Surveys, Ref. A-4, that "A few (machine) tools were overturned by the blast, but almost all of the serious damage was caused by debris from damaged buildings or by the burning of buildings." In the 1955 Nevada tests, Ref. A-3, a heavy-duty lathe (12,000 lbs) remained anchored to its slab and essentially undamaged at 10 psi.

Only an unusually rigid structure would remain standing, and substantially undamaged, at this level of blast overpressure. In contrast, one large boiler of Olive View Hospital in San Fernando was moved 3.5 ft by the 1971 earthquake, causing a fire as the gas burners were ruptured, yet the enclosing building was left standing (Ref. A-5). The building's damage level was considered serious by seismic standards because of snapped cross bracing and cracked reinforced concrete walls, yet it would be classified as light-to-moderate damage in terms of nuclear blast.

Seismic-induced equipment vibration and furniture translation within buildings is a significant source of secondary fires. Earthquakes and blasts create damage via different mechanisms, and the secondary fires they cause should be expected to be different in terms of incident rates and time-dependent fire causes. Statistical comparisons between the two are dubious.

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SECONDARY FIRES

1971 San Fernando Earthquake (Magnitude 6.6, Intensity XI)

The best available data on the incidence and immediate causes of earthquake-caused fires in the United States have been collected from several different sources for the 1971 San Fernando earthquake. From an analysis of individual fires it is apparent that most of these fires were caused by two basic types of damage mechanisms: (1) Imposed deformations on utility lines and structures, caused by earth movement; (2) Inertia effects on appliances and other furniture. Neither of these damage mechanisms is directly relevant to the topic of blast-caused fires. At short ranges where blast-induced ground motion is significant, other blast effects are overwhelmingly predominant. The fact that blast-induced ground motion was not significant in the cases of Hiroshima and Nagasaki was noted by the Strategic Bombing Survey (Ref. A-4), and McAuliffe and Moll (Ref. A-6) extended this generalization to include ground bursts and air bursts.

A third category of earthquake-caused fire mechanisms is deformation of the structure, which in turn ruptures gas and electrical services. This was not a significant cause of earthquake fires in 1971, as in the previous two categories, but ostensibly it presents a closer analogy with the blast-induced damage. Similar to blast-caused ground motion, other predominant nuclear weapons effects are present, blast-induced structural deformations including windows and doors blown in, and a large amount of flying debris has been created.

Consider the five causes of earthquake-caused fires in the 1971 San Fernando earthquake as shown in Tables A-2 and A-3. The electrical and gas categories together account for about 85% of the total. As discussed further, these five mechanisms are not similar enough to the blast situation to warrant extensive statistical explanation of the data; however, a valid generalization is made. The electrical and natural gas distribution systems probably constitute the major potential source of blast-caused fires.

Electrical fires caused by downed wires, damaged transformers, and crossed wires are directly comparable to a blast environment. Widespread damage of this

TABLE A-2

SPECIFIC CAUSES OF FIRES DUE TO THE 1971 SAN FERNANDO EARTHQUAKE

	INSIDE BUILDINGS		OUTSIDE		TOTAL	
	NUMBER	% OF TOTAL	NUMBER	% OF TOTAL	NUMBER	% OF TOTAL
ELECTRICAL	27	33	9	11	36	44
GAS	28	34	4	5	32	39
CHEMICAL SPILL	6	7	0	0	6	7
DEBRIS	5	6	0	0	5	6
BROKEN FLUE	3	4	0	0	3	4
TOTAL	69	84%	13	16%	82	100%

Note: While 120 fires were attributed by investigators in 1971 as being earthquake-caused, records documenting the type of immediate cause are available for only 82 of these fires, or about 70% of the total. These 82 fires are tabulated above. "Debris includes minor falling objects that came into contact with heaters or other similar light or no damage situations. None of these debris fires was due to major damage or "debris" in the usual Civil Defense context.

Sources: Pacific Fire Rating Bureau files, courtesy H.C. Bigglestone, dispatching logs and fire reports from the following Fire Departments: Los Angeles City, Los Angeles County, Burbank, Pasadena, Glendale, South Pasadena, Alhambra, Orange County, San Fernando, Arcadia, Vernon, Crest Forest, and San Marino.

TABLE A-3

BREAKDOWN OF 1971 SAN FERNANDO EARTHQUAKE-CAUSED
BUILDING FIRES ATTRIBUTED TO ELECTRICITY

	NUMBER	%
EXTERIOR WIRES	3	16
AIRCONDITIONER OR HEATER	10	53
LIGHTS	4	21
WASHING MACHINE	1	5
EXTENSION CORD	1	5
TOTAL	19	100

Note: While approximately 7 documented earthquake-caused building fires had damage to electrical systems as their proximate cause, the specific type of electrical ignition involved is known for only 20 cases.

BREAKDOWN OF 1971 SAN FERNANDO EARTHQUAKE-CAUSED
FIRES WITHIN BUILDINGS CAUSED BY NATURAL GAS

	NUMBER	%
HEATERS	6	46
WATER HEATERS	5	38
BOILER	1	8
RANGE	1	8
TOTAL	13	100

Note: While 28 documented earthquake-caused building fires had natural gas leaks as their proximate cause, the precise type of gas appliance involved is known for only 16 cases.

type can be expected, since overhead wires are downed and timber poles damaged at about 3 psi overpressure (Refs. A-3 and A-4). It should be noted that while overpressures are used for comparison, it is wind or dynamic pressure at these overpressure levels that actually damage wires and poles. In the San Fernando earthquake most wires either fell without shorting, were not energized, or failed to ignite the surface they landed upon. Of the 13 fires that resulted most were small and easily extinguished. This small number of fires is important since in the entire San Fernando area there were an estimated total of 7,500 downed electrical wires and over 300 damaged transformers.

From this data it could be concluded that overhead electrical distribution systems are relatively vulnerable to earthquakes, but fires due to this type of damage may not be a major problem. Would more fires result from damage to exterior electrical distribution lines in a blast situation? The answer is likely yes, assuming the utility system's grid is energized (a factor further discussed below), and because there will be more debris for potential ignition, and more extensive wires and transformers damaged. The blast event may de-energize portions of the local transmission grid, or interruption may occur because of damaged substations or major high voltage transmission lines.

Natural gas was the other major cause of fires in the San Fernando earthquake. Damage occurred at distribution line locations outside buildings. This would not be expected to occur in a blast environment, since underground lines are more vulnerable to earthquakes than to blast. It is more likely for buried gas mains and service lines to remain undamaged in the case of blast, and the number of fires in structures would increase, with rupture of services at building perimeters.

In San Fernando there were many more gas line leaks than fires caused by the leaks. There were numerous exterior gas line leaks, and there were only six documented fires in this category. There were more gas-caused fires inside buildings (34) than outside (6). This is analogous to electrical failures: gas leaks produce fuel, but ignition sources outside may not be present; electrical shorts or "leaks" present an ignition source, but there was no fuel.

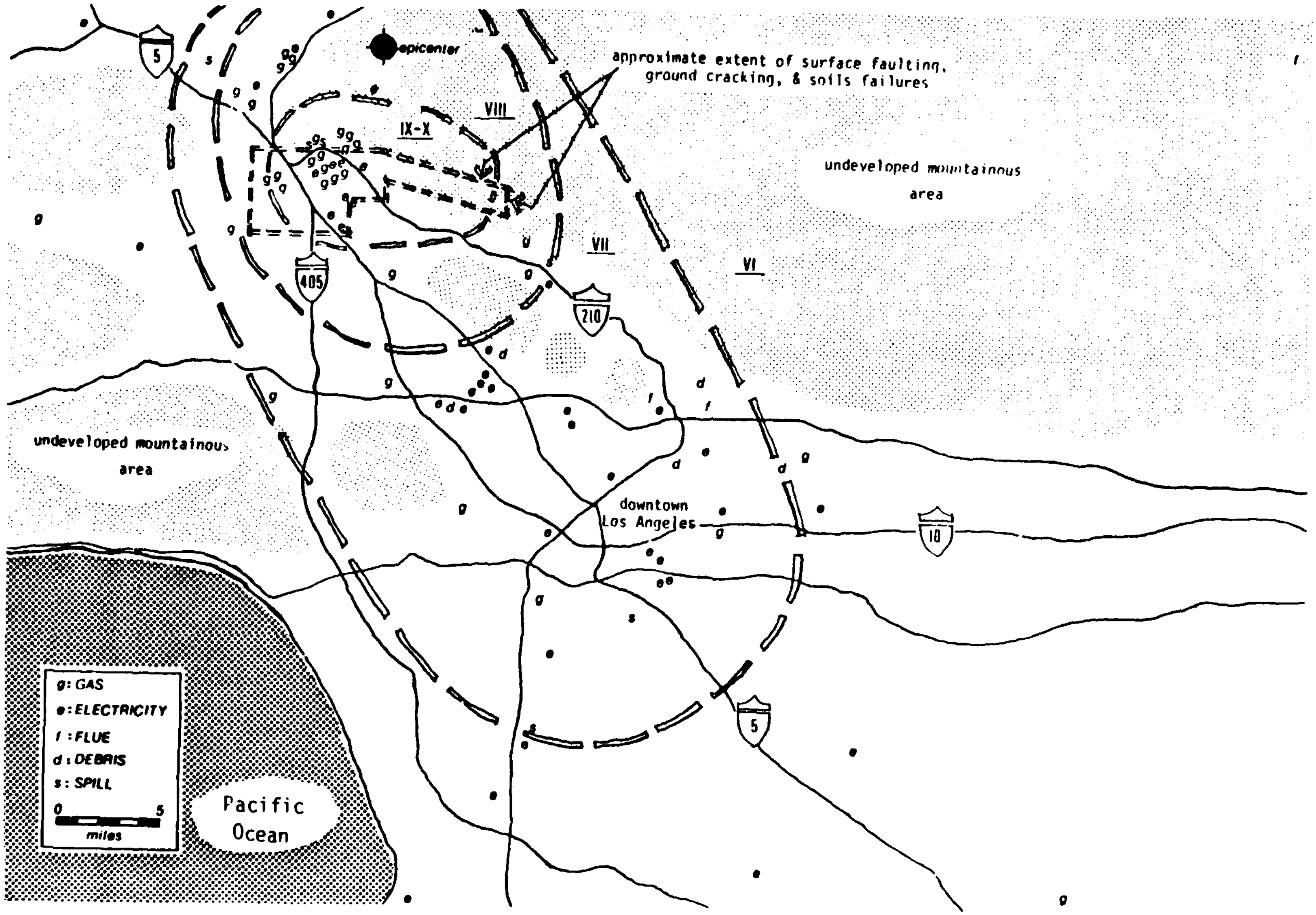

Fig. A-2. Location of Earthquake-Caused Fires in the 1971 San Fernando Earthquake.

Natural gas fires within buildings due to the San Fernando earthquake were apparently created by the inertial forces acting on heaters and other free-standing objects. This type of nonstructural earthquake damage can easily occur with little or no structural damage. The 1971 San Fernando data show fires occur in buildings that have suffered only minor or moderate damage. As shown by Figure A-2, more fires occurred in areas of heavy ground shaking than elsewhere, but occasional fires occurred at distant locations. In a blast environment, if water heaters or appliances have moved, there is probably significant damage to the rest of the structure.

Tangshan, China 1976. (Magnitude 7.8)

Information is limited, but there were few fires primarily because there was no widespread distribution network of pipes for natural gas. The university library ignited and burned to the ground. Several minor explosions and fires that originated in uncontrolled chemical reactions occurred in some factories. Power transformers were shifted off their bases, cracking oil seals, which lead to arcing and ignition of the insulation oil. Electric power was soon lost following the quake. Water pipes buried in the ground were severely damaged and no pressure remained in the distribution lines for fire fighting. All standing towers were destroyed, and reservoirs emptied in the quake.

Some important data emerge on seismic damage to buried pipes as a function of pipe diameter and the resulting number of breaks per length of pipe. The larger the pipe diameter in general, the fewer the number of breaks per kilometer. This is significant in the consideration of potential blast damage to gas pipelines and the release of gas pipeline contents to provide a source of fuel for blast-induced, secondary fire ignitions.

From the Tangshan vicinity the following data are noted:

Buried Steel Gas Pipeline Damage

Pipe Diameter	Breaks per Kilometer
50 to 100 mm	1.6
530 mm	0.31

Cast iron or mortar pipes of 150 to 300 mm diameter were all badly damaged.

Water Pipeline Damage

City Location	Pipe Diameter (mm)	Breaks per Kilometer
Yinkou	100	1.8
	150	0.88
	300	0.13
Tianjin	50	1.13
	75-600	0.2
	600	0.04
Tangshan	150	5.23
	300	4.63
	600	1.89

Conclusions reached on seismic damage to buried pipes are: the greater the diameter the fewer breaks per kilometer; blast-induced ground shaking and subsequent breaks of gas pipelines should follow the same trend.

The following additional earthquake incidents were investigated and information relevant to earthquake-induced fires was extracted were possible. A general survey of these selected incidents shows clearly that there is no simple correlation between damage and the number of initial fires. It was noted, however, that, when utilities were cut off to structures by line breakage or deliberately, the number of fire incidents decreased markedly. The presence and extent of the utility distribution and control systems, gas and electricity, are basic factors in determining the number and severity of earthquake-caused fires.

Campania, Italy - November 1980 (Magnitude 7.0, Intensity X)

With over 4,000 deaths and extensive damage to stone construction buildings, there was only one reported fire in a damaged building.

El-Asnam, Algeria - October 10, 1980 (Magnitude 7.2, Intensity IX to X)

Electrical transformers were overturned and destroyed, which led to total loss of electricity. Water was turned off at the pumping station since many breaks resulted in no useful pressure buildup in the water lines.

However, since a major ignition source was eliminated early, no serious fires were started/reported. Reporting may have been hampered, since the communication building was severely damaged and the contents destroyed.

Sharpsburg, Kentucky - (Magnitude 5.3, Intensity VII)

Major damage occured to 27 businesses and 59 residences. Minor damage occurred to 10 businesses and 210 residences. No fires occurred.

Livermore, California - January, 1980 (Magnitude 5.5, Intensity VII)

Of the 900 trailers in the area, over 100 were knocked off their foundations. At one mobile home park, 95 out of a total of 133 units were severely damaged. No fires were reported.

Ponta Delgada, Azores - January, 1980 (Magnitude 7.0, Intensity VII)

Although 20,000 people were made homeless and residential damage was extensive, utilities were lost quickly, but no fires were reported.

Jakarta, Indonesia - December 19, 1979 (Magnitude 6.1)

Approximately 22,000 homes were destroyed and 71,000 persons were made homeless, yet no fires were reported.

Mashad, Iran - November 14, 1979 (Magnitude 6.7)

Hundreds of residences were destroyed, utilities were rapidly lost, but no fires were reported.

Imperial Valley, California - October 15, 1979 (Magnitude 6.6)

In this earthquake two residences collapsed and 1,565 residences and 103 mobile homes were damaged. Five out of six fuel storage tanks failed by buckling and fuel leaks were numerous. High voltage wires were down in 10 locations, 8 line fuses were blown, 6 pole top circuit breakers were damaged and a heat exchanger at a geothermal plant was destroyed. One reported fire occurred at a mobile home park.

Montenegro, Yugoslavia - April, 1979 (Magnitude 6.7, Intensity IX)

All electrical, gas, water, and telephone lines were damaged. The only reported fire was in a cotton storehouse following the collapse of the roof.

Guerro, Mexico - March 1979 (Magnitude 7.8)

Three storage buildings collapsed and hundreds of buildings were severely damaged. In addition, 60% of the university buildings were badly damaged, yet no significant fires were reported.

Oaxaca, Mexico - November 1978 (Magnitude 6.5)

In this incident, in which hundreds of buildings were damaged, all utilities and communications were lost; only four fires were reported.

Stuttgart, Germany - (Magnitude 5.7)

Hundreds of buildings were damaged and no fires were reported.

Santa Barbara, California - August 1978 (Magnitude 5.1)

In this earthquake, one mobile home was destroyed, 219 had major damage, and 104 had minor damage. Damaged high voltage lines did start some roof and grass fires and one home was destroyed because of a water heater caused fire.

Salonika, Greece - June 1978 (Magnitude 6.4, Intensity VII)

Much structural damage occurred. An 8-story building and eight 2-story buildings collapsed. In a city of 46,440 buildings, 13,252 required repair, and 3,204 collapsed. Of the 2,322 factory buildings, 276 had heavy damage and an additional 136 needed repair. No significant fires were reported.

Sendai, Japan - June 1978 (Magnitude 7.5, Intensity VIII)

In this incident, in which 48,000 residences were damaged (4,800 more than 50% damaged), 10 fires were reported.

Alaska - February 1978 (Magnitude 7.5)

There was minor damage to a sparsely inhabited region, and no fires were reported.

San Juan, Argentina - November 1977 (Magnitude 7.4)

About 40,000 persons were left homeless; however, since all utilities were destroyed, no fires were reported.

Bucharest, Romania - March 1977 (Magnitude 7.2, Intensity VIII)

The only information available is that a few minor fires were caused by damaged power lines. All were quickly extinguished.

Mindanao, Philippines - August 1976 (Magnitude 7.9)

In this incident 12,183 persons were made homeless, 3,564 were killed, and 8,556 were injured. No fires were reported.

Fruili, Italy - May 1976 (Magnitude 6.5)

The roofs of 10 industrial buildings collapsed and two hospitals suffered wall damage. No fires were reported.

Lice, Turkey - September 1975 (Magnitude 6.9, Intensity VIII)

In this event 5,518 homes were either collapsed or heavily damaged, 1,477 had medium damage, and 1,536 were lightly damaged. No fires were reported.

Managua, Nicaragua - December 1972 (Magnitude 6.2)

While there was extensive damage, 5,000 deaths, and more than a billion dollars damage, there were few initial fires. A major fire occurred after fires were deliberately set to eliminate the spread of disease in the rubble.

Caracas, Venezuela - July 1967 (Magnitude 6.5)

Several reinforced concrete buildings collapsed and hundreds more were damaged. No fires were reported.

Niigata, Japan - June 1964, (Magnitude 7.7)

There were two oil tank leak fires and nine minor residential fires. Local water reservoirs were breached, which resulted in a measure of self protection caused by water flooding potentially ignitible debris. The city gas supply was shut off immediately following the quake.

Anchorage, Alaska - March 1964 (Magnitude 8.4)

In this event over one billion dollars of damage was done; 131 people were killed. There were three building fires, a transformer fire, and several oil storage tank ruptures that caught fire as well.

Fukui, Japan - June 1948 (Magnitude 7.3)

In the city having 15,525 residences, 12,425 were collapsed, 1,859 were eventually burned. Only 13 fires were initially reported.

Imperial Valley, California - May 1940 (Magnitude 7.1)

Four fires were caused by the earthquake; damage was heavy to poorly built masonry structures, but many other buildings, such as the 15 "Field Set" schools, were undamaged. Property loss totalled $33 million. The 1950 Imperial Valley event was quite similar in terms of ground motion and there was more development at risk, yet it caused only one fire.

Long Beach, California - March 1933 (Magnitude 6.3, Intensity IX)

An estimated 32 earthquake-caused fires occurred in the city of Long Beach; about half of these fires were caused by gas leaks.

Santa Barbara, California - June 29, 1925 (Magnitude 6.3, Intensity IX)

In this event one fire occurred in a residence, however, employees at the central natural gas and electrical plants shut off all services before the shaking had stopped (about 15 seconds), which may have prevented some fires. Of the non-dwelling buildings, 180 were severely damaged or collapsed, 140 moderately damaged, and 199 slightly damaged.

Kanto, Japan - September 1, 1923 (Magnitude 8.3, Intensity X)

One source of data on this event lists 88 fires, another 134. Seventy-seven of these fires are reported to have spread, with some of these causing the Tokyo-Yokohama conflagration, which accounted for most of the damage. Thirty-four thousand buildings were destroyed by the earthquake and 375,000 by fire. Approximately 99,000 lives were lost.

A summary of the above earthquakes as well as those noted in Ref. A-6 is presented in Table A-4.

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TABLE A-4

EARTHQUAKE FIRES VS BUILDING DAMAGE

Earthquakes	Number of Fires	Magnitude (Richter)	No. of Buildings Damaged Collapsed	Badly	Slightly	Total	Lives Lost
San Francisco, CA 1906	12	8.3	1.3K	-	-	1.3K	700
Kanto, Japan 1923	88-134	8.3	128K	126K	130K	384K	99K
Santa Barbara, CA 1925	1	6.3	180	140	199	519	13
Caracas, Venezuela 1967	0	6.5	8	200	-	208	277
Managua, Nicaragua 1972	0	6.2	-	-	-	-	5K
Lice, Turkey 1975	0	6.9	5.5K	1.5K	1.5K	8.5K	2.4K
Fruili, Italy 1976	0	6.5	-	-	12	12	929
Long Beach, CA 1933	32	6.3	-	-	22K	22K	100
Fukui, Japan 1948	13	7.3	6K	11.8K	-	17.8K	5.4K
Eureka, CA 1954	3	6.5	0	0	1K	1K	1
San Francisco, CA 1957	1	5.3	0	0	5K	5K	0
Concepcion, Chile 1960	3	8.3	800	3.6K	8.4K	12.8K	5K
Anchorage, Alaska 1964	6	8.5	372	-	2.5K	2.9K	114
Niigata, Japan 1964	9	7.4	-	-	10K	10K	26
San Fernando, CA 1971	120	6.6	-	6.8K	28.5K	35.3K	58
Tangshan, China 1976	-	7.8	504	412	200	1.1K	240K

TABLE A-4 (Cont.)

EARTHQUAKE FIRES VS BUILDING DAMAGE

Earthquakes	Number of Fires	Magnitude (Richter)	No. of Buildings Damaged Collapsed	Badly	Slightly	Total	Lives Lost
Imperial Valley, CA. 1940	4	7.1	-	-	-	-	9
Mindanao, Philippines 1976	0	7.9	-	-	-	-	3.6K
Bucharest, Romania 1977	-	7.2	35	-	-	-	1.5K
San Juan, Argentina 1977	0	7.4	-	-	-	-	70
Sendai, Japan 1978	10	7.5	-	4.8K	43.2K	48K	21
Salonika, Greece 1978	0	6.4	3.5K	20.3K	59.1K	82.9K	50
Guerro, Mexico 1979	0	7.6	3	-	-	-	-
Imperial Valley, CA 1979	1	6.6	2	-	1.7K	1.7K	0
Ponta Delgada, Azores 1980	0	6.8	-	-	-	-	4
Eureka, CA 1980	1	7.0	-	-	-	-	0
Livermore, CA 1980	0	5.5	0	95	5	100	0
Sharpsburg, Kentucky 1980	0	5.3	0	86	220	306	0
El-Asnam, Algeria 1980	0	7.2	-	-	-	-	3.5K
Campania, Italy 1980	1	7.0	-	-	20K	20K	3K

APPENDIX B

Tornadoes and Wind Experience

Appendix B
TORNADOES and WIND EXPERIENCE

Nature's most intensive storm, the tornado, provides a limited yet useful analogue to the damage caused by nuclear blasts and the establishment of conditions that could lead to secondary fires.

Contrary to the conclusions reached in Ref. B-1 (McAuliffe & Moll) the major damage mechanism of a tornado is the high wind speed as opposed to the effect of a low pressure cell that makes up the inner vortex region of the funnel (Ref. B-2). Fujita (Ref. B-3) uses a six-level scale to delineate expected damage. These are shown in Table B-1 along with the dynamic pressures for each scale. As may be observed in Table B-1, at the overpressure range of major interest; i.e., 2 to 5 psi, the dynamic pressures are in the range of 0.1 to 0.6 psi. Typical tornadoes fall in the F-3 category, with wind velocities around 200 miles/hr. At this wind velocity, damage to drag targets corresponds to what would be expected at the 12 psi overpressure range, although the signature or duration is perhaps 10 times longer. Hence, low pressure regions of the tornado vortex moving over a building region, while having values as much as 5 psi below local atmospheric pressure, simply results in air from higher pressure regions inside the building quickly leaking through ever-present cracks or openings (windows, doors, louvers, vents, etc.) rather than "exploding" the building. This latter situation (exploding via pressure relief) would only occur if the tornado-enveloped building were perfectly sealed, a highly improbable condition (1 in 11,000 buildings is suggested in Ref. B-2).

The tornado-damaged buildings look as if they exploded because, while windward walls are exposed to the inward forces of the incident winds, there are outward forces on the leeward walls, the side walls, and the roof, and the resultant forces are responsible for extensive damage when wind speeds are high.

TABLE B-1: FUJITA SCALE FOR DAMAGING WIND

Scale	Miles per hour	Expected Damage	Dynamic Pressure (psi)
F - 0	40 - 72	light	0.03 to 0.12
F - 1	73 - 112	moderate	0.12 to 0.27
F - 2	113 - 157	considerable	0.27 to 0.53
F - 3	158 - 206	severe	0.53 to 0.92
F - 4	207 - 260	devastating	0.92 to 1.6
F - 5	261 - 318	incredible	1.6 to 2.5

On Wednesday, April 3, 1974 a tornado storm hit the town of Xenia, Ohio (population 27,000). The storm had a path width of one-half to three-quarters of a mile, a forward progress speed of 45 miles per hour, and vortex winds estimated to be 320 miles per hour, (as compared with "usual" tornadoes, whose path widths are 200 to 300 yards, forward speeds of 15 mph, and wind speeds of about 200 mph). The Xenia tornadoes would be rated F-5, "incredible damage", on the Fujita Scale. In 10 minutes, a tornado storm whose funnel clouds did **not** even descend to the ground, destroyed 1,347 buildings, 47% of the city tax base (primarily one-story residences of wood frame and brick veneer, slab on grade construction), killed 33, injured more than 1,000, derailed a train, destroyed 4,000 cars, uprooted most trees, and covered almost every street in the path area with debris. Numerous waterline breaks resulted in a total loss of water pressure in the area.

Of significance to the secondary fire problem, Chief John L. Troeger of the Xenia fire department reported **no serious fires occurred** in the first 24 hours following the disaster (Ref. B-4). This was in spite of the fact that an estimated 400 to 500 natural gas leaks made it impossible to breathe in locally damaged areas. (Rather than follow a futile attempt to shut off individual service, the utility company shut off all gas to the city). There were a couple of reasons that fires did not occur. First, wind-carried debris destroyed the electrical and telephone distribution systems, removing many souces of ignition; and second, heavy drenching rains immediately followed the tornadoes, further reducing any chances for serious secondary fires.

It can be concluded from this exceptional tornado event that forces induced by winds, dynamic loads, or peak overpressures from blast waves in the same 2 to 5 psi magnitude do result in great structural damage to buildings. Gas and water pipeline connections are broken, overhead electrical wires are knocked down, and enormous quantities of combustible debris are created. By virtue of the simultaneous events (drenching rains, winds to blow out poorly initiated fires started by lightning preceding the tornado, or downed wires arcing prior to line fuses or breakers deenergizing the lines), tornado-caused fires are very unlikely phenomena, and the Weather Bureau storm data summaries support this conclusion. Under the nuclear weapon blast scenario, however, drenching rains immediately following the event are

not likely and it is possible that blast-generated natural gas leaks, at least one every three damaged buildings (based on Xenia data), could be ignited and result in serious secondary fires.

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APPENDIX C

Stochastic Secondary Fire Model

Appendix C
STOCHASTIC SECONDARY FIRE MODEL

Because the secondary fire model was developed with a relatively small data base, which required considerable analysis and engineering judgment, it was decided to provide a statistical approach that will permit an estimate to be made of the accuracy of the model and the variance introduced by the use of the small amount of data available.

It is proposed that the occurrences of secondary fires be analyzed statistically using the "Parzen" (Ref. C-1) method of applying the Poisson distribution. The number of occurrences of an event in a continuum of unitized time, length, area, or space is defined such that one unit of the continuum represents an event of this type occurring randomly, at a mean rate of λ per unit. The continuum can then be described by the Poisson distribution shown below:

$$p_X(x) = e^{-\lambda} (\lambda^x/x!)$$

where $\lambda > 0$

$x = 0, 1, 2, . . . n$

and $p_X(x) = 0$ otherwise;

and the characteristic function is

$$\phi_X(u) = e^{\lambda(e^{iu}-1)}$$

with the expected value $E[X] = \lambda$

and the variance $Var[X] = \lambda$

Events are described as being distributed randomly in a continuum if they occur in accordance with the Poisson process. Figure C-1, from Benjamin and Cornell (Ref. C-2), shows typical probability density functions for the Poisson distribution with various values for λ. In the context of secondary fires, these distributions can be viewed as the probability of a varying number of fires in a particular region caused by a disaster such as an earthquake or a nuclear attack. The individual bars shown on the graphs give the various probabilities or varying numbers of fires within the region of interest; i.e., two fires (x = 2), four fires (x = 4), or no fires (x = 0). It is interesting to observe that, as the particular λ, or mean rate, is increased, the distribution tends to become more symmetrical about the mean.

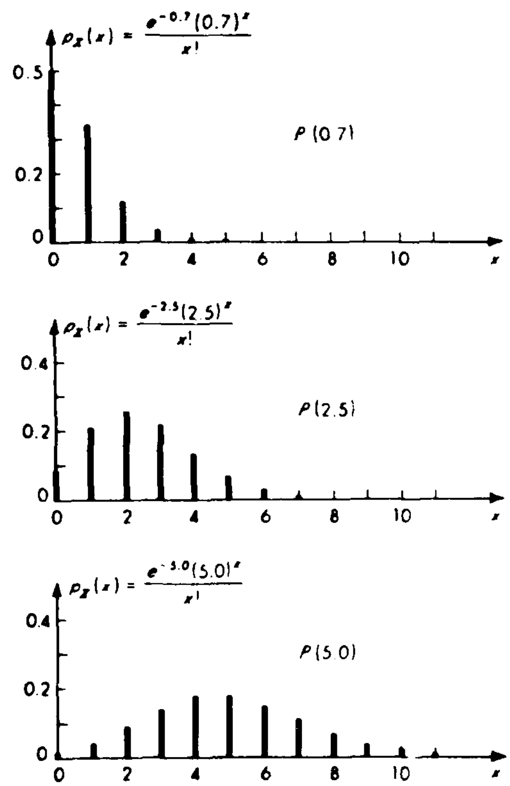

Fig. C-1. Poisson Distribution.

The Poisson process is basically a counting process in a time or distance continuum and is generally considered in the time domain. Thus, the variable, t, is introduced in the formula shown below using the Poisson counting process, N(t) for t greater than 0.

$$P_n(t) = e^{-vt} [(vt)^n/n!]$$

where $vt > 0$

$n = 0, 1, \ldots$

and $P_n(t) = 0$ otherwise;

and $[N(t)] = vt$ and, $Var[N(t)] = vt$.

The versatility of the method allows t to be replaced with distance, space, or any other convenient measure. The Poisson process can consider many random events, such as the arrival of customers for service, the arrival of alpha particles from a radioactive source at a Geiger counter, and the occurrences of such events as accidents, breakdowns, or secondary fires.

The Poisson process has been used in developing theories for the distribution of galaxies in the stellar system or for the distribution of centers of population, such as animals or epidemics, where the centers of such galaxies or populations are conveniently regarded as points distributed randomly in space. For each region, R, in a space, S, we could let the variable N(R) denote the array of points to be distributed according to a stochastic mechanism for every region, R, in space, S. N(R) is then a random variable distributed in accordance with the Poisson process with an intensity of ν. Figure C-2 depicts the stochastic mechanism applied to secondary fires in a region, R, in a sector space, S.

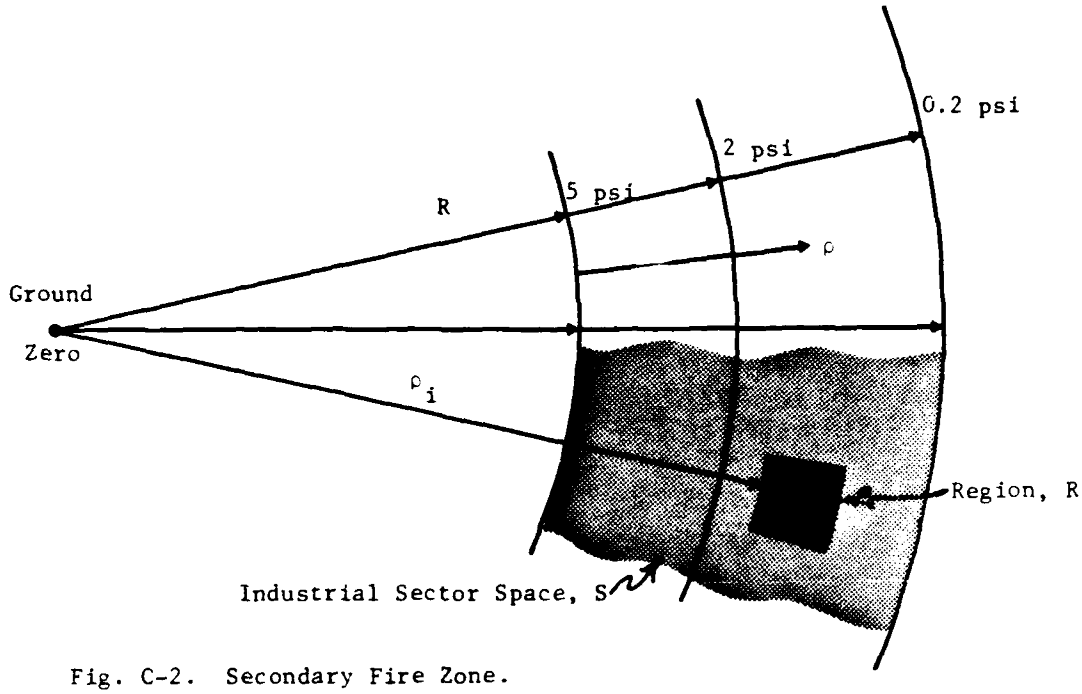

Fig. C-2. Secondary Fire Zone.

The application of the Poisson process to secondary fires has been simplified a great deal. The occurrence of secondary fires is not limited to region or space, but is dependent on other factors. Referring to Figure C-2, if region R is moved radially outward from the center of a nuclear blast, the potential damage to the region and any buildings within the region is changed. Potential building damage can be described as a damage function, shown as Figure C-3.

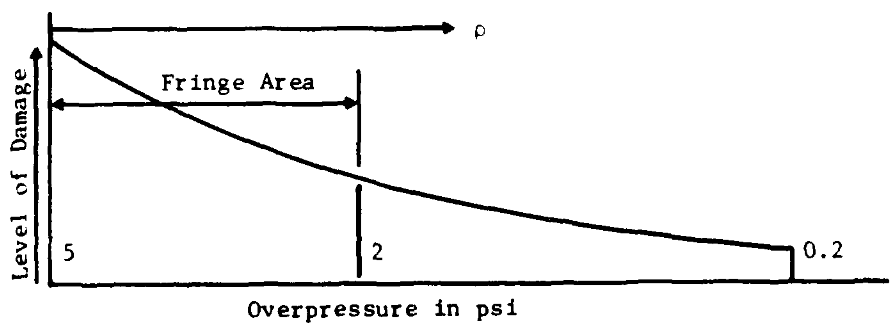

Fig. C-3. Building Damage Function.

The outward movement of Region R changes the probability at every location of the building damage causing a potential secondary fire; i.e., another building damage function. Other factors that affect the overall secondary fire potential, other than building type and location, are location and amount of debris, equipment in the building, material stored in the building, and other structures in the vicinity. These factors may be labeled as a Contents Damage function and will affect the probability of secondary fire by providing additional ignition sources.

These functions change as we move from site to site within an industrial sector space, and the change in character of the building and its contents can be described as more complex damage functions, D_B and D_C:

- Building Damage Function

$$D_B = \beta_1 e^{-\alpha_1 \rho}$$

where β_1 and α_1 are constants that are a function of building type and describe the rate of secondary fires in the building type at a particular damage level.

- Contents Damage Function

$$D_C = \beta_2 e^{-\alpha_2 \rho}$$

where β_2 and α_2 are constants that are a function of the above-ground debris and fire source materials.

Further, each region (R) of space (S) in the industrial sector (see Figure C-2) will have different sets of constants such that

$$v(\rho) = f(A_i, D_{Bi}, D_{Ci}), \quad \text{and} \quad A_i = \rho d\rho d\theta$$

or

$$v(\rho) = \beta A_i D_{Bi} D_{Ci}$$

$$v(\rho) = \beta \rho d\rho d\theta \beta_1 e^{-\alpha_1 \rho} \beta_2 e^{-\alpha_2 \rho}$$

or

$$v(\rho) = \beta \beta_1 \beta_2 \rho d\rho d\theta e^{-\rho(\alpha_1 + \alpha_2)}$$

and for a particular location,

$$\text{Let } K_i = \beta\beta_1\beta_2\,\rho d\rho d\theta \quad \text{and} \quad k_i = \alpha_1 + \alpha_2$$

such that

$$\nu(\rho) = K_i\, e^{-\rho k_i}$$

an intensity function is derived.

The above formulation provides a generalized, non-homogeneous compound Poisson process after Parzen (page 124f). Note that we have modified the original intensity function: $v(t)$ is now $\nu(\rho)$, where ρ is a distance measured radially from the 5 psi overpressure level. In the above derivation, the building damage functions and the contents damage functions are decay functions as the radial distance, ρ, increases outward from the 5 psi isobar. The area function provides a very general region of interest, and this region varies with changes in building type. At this stage we have illustrated the area function as a continuum in space. It may be more convenient ultimately to illustrate it as a discrete function; thus, the subscript i's are selected for the constants K_i and k_i. A summation using computer methods may be in order instead of the continuum or interval approximation that we are about to develop. From the intensity function above (i.e., $\nu(\rho) = K_i e^{-\rho k}$) the stated non-homogeneous Poisson process can be described using a characteristic function and a mean value function as shown below:

Characteristic function

$$\phi_{N(\rho)}(u) = \exp[m(\rho)\;(e^{iu}-1)]$$

with the mean value function

$$m(\rho) = \int_0^\rho \nu(\rho')d\rho'$$

or in our terms

$$m(\rho) = \int_0^\rho K_i e^{-\rho' k_i}\, d\rho'$$

In a sense, the foregoing derivation describes the basic random distributions of secondary fires scattered over an area, or in our case, the industrial sector space. The distribution has been modified to describe the location in the sector, the type of building, the contents of the building, and the respective building locations within the sector. The linear integration performed; i.e., movement of ρ radially, is basically an illustration of mathematical filtering, and the result in our case is a filtered, non-homogeneous Poisson process.

The additional complication or sophistication is introduced by using the K_i and k_i coefficients, which describe the various building sites, building contents, and damage functions. These are treated as random variables and provide distributions based on data available. Thus, a person who was not familiar with a particular region in a sector space could statistically treat the region or regions by utilizing a generalized, filtered, non-homogeneous Poisson process. This is illustrated in the formula below:

Let $[N(\rho), \rho \geq 0]$ be a non-homogeneous Poisson process, whose mean value function $m(\rho) = E[N(\rho)]$ possess a continuous derivative

$$v(\rho) = (d/d\rho)m(\rho)$$

Note that $v(\rho)\,d\rho$ is approximately the probability that in the time interval $[\rho, \rho + d\rho]$ exactly one jump will occur in the process $N(\rho)$. Let $[X(\rho), \rho \geq 0]$

$$\log \phi_{X(\rho)}(u) = \int_0^\rho v(\rho')E[e^{iuw(\rho,\rho',Y)} - 1]d\rho'$$

$$E[X(\rho)] = \int_0^\rho v(\rho')E[w(\rho,\rho',Y)]d\rho'$$

$$\mathrm{Var}[X(\rho)] = \int_0^\rho v(\rho')E[w^2(\rho,\rho',Y)]d\rho'$$

and Y is a random variable containing the random and/or non-random constants in the earlier formulation.

Since an industrial complex is generally in discrete increments; i.e., on an industry-by-industry basis, the relationships are:

$$\nu(\rho) = K_i e^{-\rho k_i}$$

$$\lambda_i = K_i Y_i$$

where Y_i is random or not as the case may be, and the process can be treated as a summation.

$$E[X(\rho)] = \sum_{i=1}^{n} K_i E[Y_i]$$

and

$$Var[X(\rho)] = \sum_{i=1}^{n} K_i E[Y_i^2] \quad , \text{etc.}$$

In the above formula Y_i represents a random variable that contains all the statistical variations in an industrial complex sector space and its subregions, and the probability format includes the randomness of the contents, the damage, and the building types. After the coefficients are evaluated, the formulation allows for probabilistic statements using the Poisson process such that the expected values of damage or expected number of secondary fires in a particular region with a particular weapon may be estimated. An additional feature of the filtered Poisson process is its asymptotic normality. When all constants are evaluated, an approximation for the Poisson process can be described with a normal probability distribution.

Example of the Use of the Foregoing Concepts

Assume a complex (Region R_i) of buildings in an industrial sector space of 20 buildings at 0.5 psi overpressure. The building inventory consists of:

10 Class 8 buildings with Class 4.0 equipment (communication)
5 Class 5 buildings with Class 4.0 equipment (communiciation)
5 Class 5 buildings with Class 8.0 equipment (transmitting)

Using the damage evaluation chart in Section 3, page 47, and the revised alignment chart on Figure C-4:

1. Class 8 buildings with Class 4.0 equipment
2. Class 5 buildings with Class 4.0 equipment
3. Class 5 buildings with Class 8.0 equipment

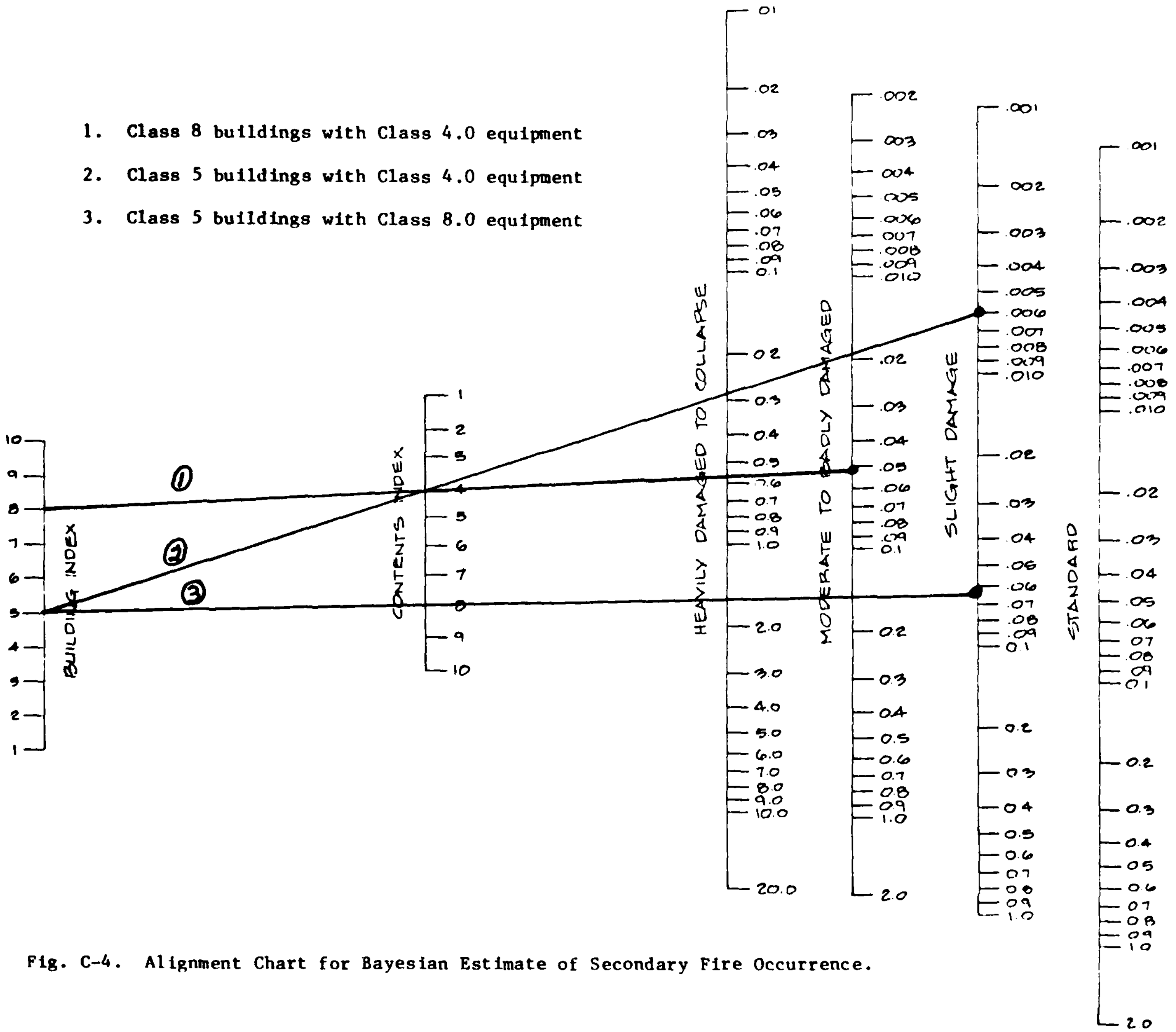

Fig. C-4. Alignment Chart for Bayesian Estimate of Secondary Fire Occurrence.

Number of Buildings	Building Class	Damage Level	Contents Rating
10	8	moderate	4.0
5	5	moderate	4.0
5	5	light	8.0

From the alignment chart we obtain the Bayesian estimate and Poisson estimate of secondary fire hazard for each building type:

Number of Buildings	Bayesian Estimate (Y_i)	Poisson Estimate (No. x (Y_i)
10	0.05	0.50
5	0.006	0.03
5	0.065	0.33

If we further assume that our Bayesian estimate is indeed **not** an estimate, but correct values, we have:

Number of Buildings	Poisson Estimate $E[X_i]$	Poisson Variance $Var[X_i]$
10	0.50	0.50
5	0.03	0.03
5	0.33	0.33
	$E[X] = \overline{0.86}$	$Var[X] = \overline{0.86}$

or mean = 0.86 and standard deviation = 0.93.

The alignment chart combines **all** of the variables in the equation

$$\nu(\rho) = K_i e^{-\rho k_i}$$

into a single value for determining the expected secondary fire occurrence. If the occurrence value is then adjusted to a rate λ by the number of each type of

building/content/pressure level. Note the tabular form of the example sums occurrences over the particular region instead of integrating, and the mean rate, λ, is a constant.

If each particular region, R, in the entire industrial complex (sector space S) were summed, the resulting number of fires would be large and would have an asymptotic normality; i.e., a normal probability distribution. Thus,

$$E[X] = 965 \text{ secondary fires, and}$$

$$Var[X] = 965, \text{ or}$$

$$\sigma_X = 31$$

which would imply that there is a 90% probability that the number of fires lies between 965 $\pm$ 1.645(31) or 914 < No. fires < 1,016.

The next concept is to treat the Bayesian estimate from the alignment chart as a random variable. Further, it is our opinion that this chart is a pioneering effort in its application, and a first estimate. ing this approach as such is highly variable. Let the coefficient of variation V_Y = 1/2

$$E[Y]/\sigma_Y = 1/2$$

and

$$E[Y^2] = \sigma_Y^2 + E[Y]^2$$

$$= (E[Y]/2)^2 + E[Y] = 1\tfrac{1}{4}\ E[Y]$$

such that

$$E[X_i] = n_i E[Y_i]$$

$$Var[X_i] = n_i E[Y_i^2]$$

where n_i is the number of buildings in the particular region of a specific type and contents index. The previous example would be changed as follows:

Number of Buildings	Bayesian Est. Mean	Bayesian Est. Var.	Poisson Mean	Poisson Variance
10	0.050	1.25(0.050)	0.50	0.63
5	0.006	1.25(0.006)	0.03	0.04
5	0.065	1 .25(0.065)	0.33	0.41
			0.86	1.08

Mean X = 0.86 secondary building fires

σ_X = 1.04 secondary building fires.

Obviously for each region (R) the estimated number of fires using this method is similarly variable. However, if we proceed further using a large number of regions as before then

$$E[X] = 965$$

$$Var[X] = 1.25\ [965]$$

$$\sigma_X = 34.7$$

In conclusion our first observation must be that the Bayesian method for determining the occurrences of secondary fires provides poor estimates for individual regions (R) within the sector space (S); i.e., $V_Y = 0.5$. However, when the final results are determined for a large industrial sector space (S) the prediction method is significantly more accurate.

Our second observation is that the asymptotic distribution of the number of fires is log-normally distributed, owing to the exponential behavior of the damage functions. However, the normal distribution differs little from the log-normal distribution for large numbers.

Table C-1 combines the foregoing computations into a simple tabular form that would permit an analysis of an entire sector.

TABLE C-1: WORKSHEET FOR ANALYZING AN ENTIRE SECTOR

Facility Type	1 Bldg Index	2 Bldg Content	3 PO	4 Damage Level	5 Bayesian Hazard Value	6 N	7=6×5 Expected No of Fires	8=6×5
Σ	X	X	X	X	X	ΣN	E[•]	Var[•]

Note: E[·] = Expected (Average) number of fires ← Σ Column 7

Var[·] = Variance in number of fires ← Σ Column 8

σ = Standard deviation = $\sqrt{\text{Var}[\cdot]}$

Approximately normally distributed for Σn large.

References

C-1. Parzen, Emmanuel, **Stochastic Processes**, Holden-Day, Inc., San Francisco, 1962.

C-2. Benjamin, Jack R. and C. Allin Cornell, **Probability, Statistics and Decision for Civil Engineers**, McGraw-Hill Book Company, New York, 1970.

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Unclassified
September 1981
120 pages

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There are significant differences between the secondary ignitions caused by nuclear blasts and those caused by other mechanical stimuli such as earthquakes. This fact greatly reduces the data base available to apply to the development of a prediction method.

A model, developed for use by civil defense planners, is detachable from the report for easy use in field surveys. The input provided includes all information required to determine the key parameters: the building type, its structural characteristics, a use classification, damage as a function of overpressure, and the probability of secondary fires.

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A model, developed for use by civil defense planners, is detachable from the report for easy use in field surveys. The input provided includes all information required to determine the key parameters: the building type, its structural characteristics, a use classification, damage as a function of overpressure, and the probability of secondary fires.

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